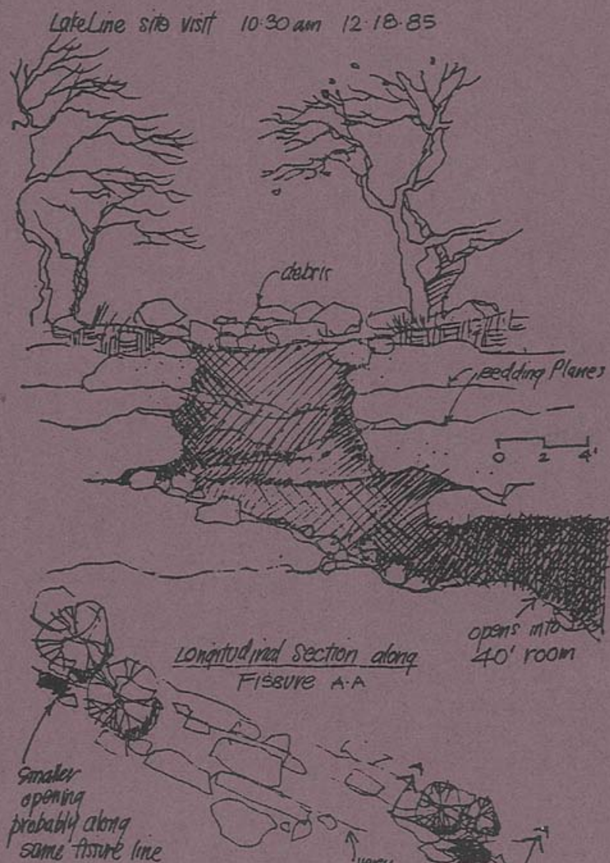
URBAN KARST

Geologic Excursions in Travis and Williamson Counties, Texas

C.M. Woodruff, Jr. and C. Lee Sherrod, Coordinators



GUIDEBOOK 16

AUSTIN GEOLOGICAL SOCIETY
P.O. Box 1302
Austin, Texas 78767

1996

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Contributions by

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James R. Reddell, James W. Sansom, Jr., Raymond M. Slade, Jr.,
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"If it form the one landscape that we, the inconstant ones,
Are consistently homesick for, this is chiefly
Because it dissolves in water."

In Praise of Limestone
W.H. Auden

Cover Illustration

Field sketch of Lakeline Cave by Robert Chipman, 18 December 1985.

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PREFACE

Karst is the term denoting landscapes formed on slightly soluble bedrock owing to processes of dissolution by groundwater. In limestone terrains, karst is expressed by erratically developed cavernous porosity and the surface manifestations thereof: sinkholes, voids of various sizes, and locally erratic surface drainage. Karst landscapes are typical of the Edwards Limestone, which occurs across a vast region of Central Texas along and west of the Balcones Escarpment, and karst processes are key to understanding the workings of the Edwards Aquifer within its various segments. In this context alone, as conduits for the transmission of groundwater, karst features and karst-related processes in Central Texas have been the subject of many scientific studies.

Even in pristine areas, karst terrains pose potential environmental uncertainties relating to issues of water quality and quantity within underground reservoirs. Karst aquifers are notable for their heterogeneity and resulting erratic aquifer properties, high volumes of groundwater flow through cavernous conduits with consequent rapid depletion and recovery, and in significant instances, the occurrence of complex underground faunal assemblages. Problems are compounded where humans occupy karst lands and change the natural process regimes. Such is the case along the Balcones Escarpment, which is an ecological borderland that provides the key resources on which human populations traditionally depend: potable water, beautiful and diverse habitats, and locally fertile soils. This natural borderland has supported human habitation since pre-Columbian times, with caves and undercut limestone ledges providing local shelter, springs and spring-fed streams providing water, and the fault-controlled borderland providing sources of food--both native plants and game. The first permanent European settlement in Texas occurred along the Balcones fault line, which localized the spring-fed upper reaches of the San Antonio River with its fertile alluvial soils and nearby sources of building stone. And Austin was established as Capital of the Texas Republic precisely because of its position along the Balcones Escarpment, its abundant potable water, and other key resources that accrued from its location along what was later recognized as a fault zone. Subsequently, cities and towns grew along this borderland, and today, the Balcones Escarpment is prime real estate. Ongoing urban/suburban-growth along Interstate Highway 35 suggests a near-term coalescence of San Antonio with Austin along an 80-mile corridor. Karst terrain lies along almost the entire length of this growth corridor, capping the hills that are readily seen west of the interstate highway.

Because of the clear issues related to growth in this part of Texas, "urban karst" has been chosen as the theme of Austin Geological Society's field trip for Spring, 1996. The geographic scope of this theme includes Travis and Williamson Counties, mostly in Greater Austin but also incorporating one locality northwest of Georgetown. The trip comprises seven stops (Figure 1) that address karst issues from three vantage points: 1) as part of the porosity system that transmits groundwater into and through the Edwards Aquifer; 2) as habitat for endangered species; and 3) as a geotechnical constraint (that is, substrate riven by solution and thereby posing problems for structures emplaced above karst voids). These issues are addressed orally during the field trip stops as well as by a series of articles presented in this volume. The article presented by Robert Mace (this volume) has no corresponding field trip stop, but it provides hydrogeologic information on the nonhomogeneous properties of the aquifer, and this pertains to many of the attributes that we view during this trip.

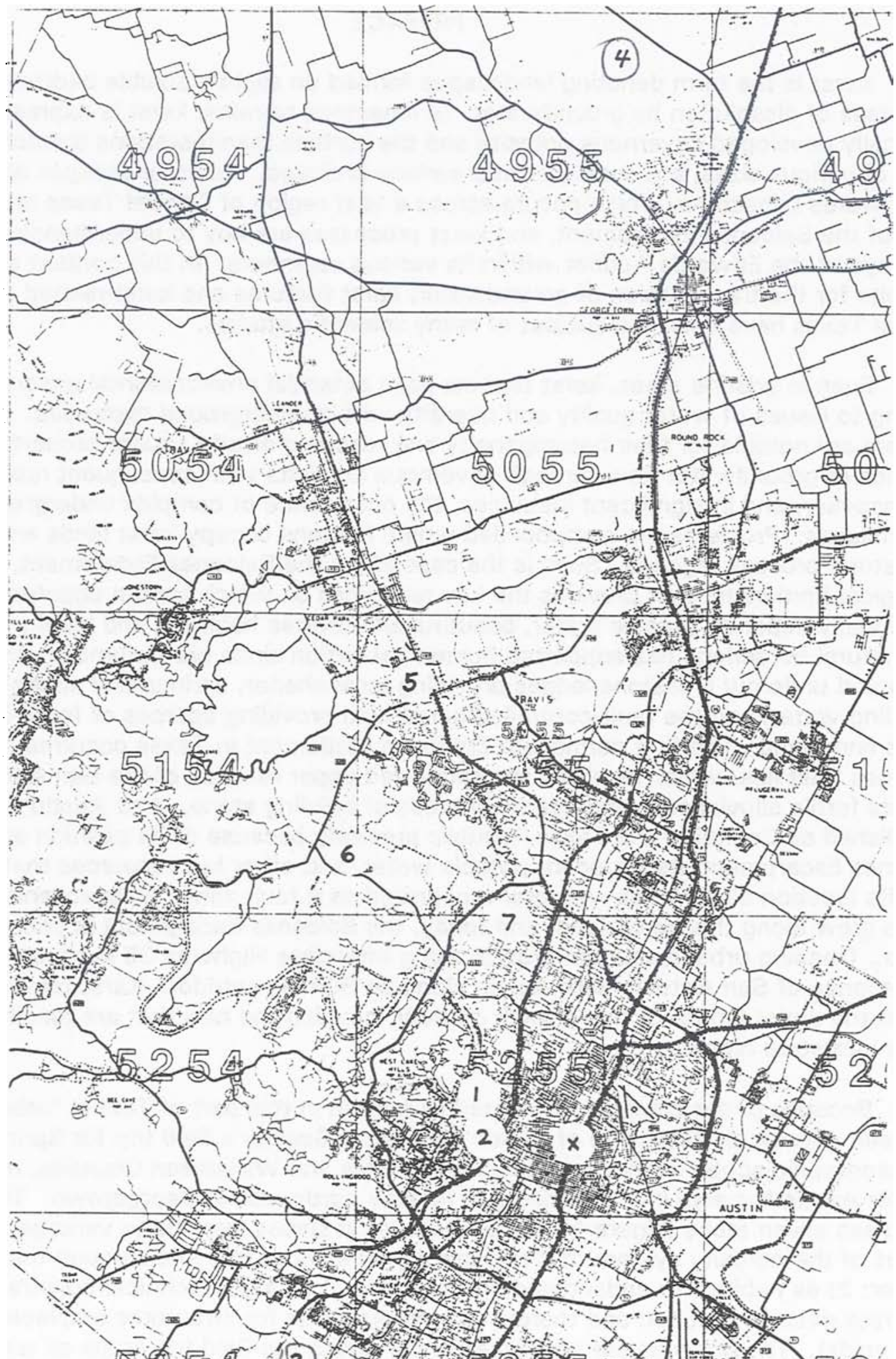


Figure 1. Urban karst field trip stops (base map from Texas Department of Transportation County Highway Maps); note, "X" marks point of departure.

A common theme among the stops is change: change in the landscape itself during the expanses of geologic time (noting that karst features and karst landscapes have "life cycles" through which they are formed and are eventually effaced); change in the land owing to human modifications; and changes in our attitudes, as we have become more aware of our local environments and the consequences of our activities.

The first stop examines karst features in West Enfield/ Tarrytown, a West Austin neighborhood that was developed mostly in the late 1940's and early 1950's. Most residents do not recognize this area as being a karst terrain or being an area that recharges the Edwards Aquifer, but sinkholes occur, and a former commercial cave, Austin Caverns, lies beneath part of this neighborhood. Austin Caverns was destroyed partly by quarrying activity and partly by collapse attendant to the construction of roads and homes. Today, as reported by James Reddell, a remnant of this cavern receives urban runoff via a city storm drain; a manhole provides access to a highly degraded chamber. Nearby, Woodruff provides a case study in which the City Board of Adjustment continues to grant "hardship" variances for densities exceeding the 45 percent allowed by current zoning laws--this despite local densities as high as eight houses per acre on a karst recharge zone.

The second stop is at Deep Eddy Pool in Eilers Park, a City swimming pool that is fed by a shallow water well. This well is presumed to produce groundwater from Colorado River terrace alluvium, but the source has not been substantiated. This stop thus focuses on the part of the Edwards Aquifer fed by recharge within the densely developed West Enfield/Tarrytown area. Raymond Slade discusses the scant information on groundwater for this area, which has proven to be a forgotten part of the aquifer. This forgetfulness on the part of residents and civic officials has promoted ongoing environmental blunders such as variances beyond (already high) ordinance-prescribed housing densities and urban storm drains connected to caves.

The third stop is on the karst terrain in far South Austin within the Slaughter Creek watershed--an area that is known to be part of the recharge zone to the Barton Springs Segment of the Edwards Aquifer. Unlike densely developed Tarrytown, this area is being transformed from ranch land to various urban/suburban uses, but it is being developed with acute awareness of the sensitive conditions in the area. And unlike Tarrytown, development in this area is under the watchful eye of various regulatory and oversight authorities, whose concerns are aquifer protection. Here we view examples of planning and engineering design aimed at using this terrain without appreciable adverse impacts. A visit to the National Wildflower Research Center reveals a facility planned and built with full awareness of local karst features and the sensitive position of the site with respect to the aquifer. The multiple strategies employed to realize the tract's maximum potential while minimizing environmental harm are described by Joshua Blumenfeld and David Northington. Nearby, at the intersection of LaCrosse Avenue and South Loop 1, geotechnical tests revealed the presence of karst voids along the roadway; John Wooley discusses the engineering techniques that were used to ascertain the problem and to ensure stability of a cut slope.

From Stop 3, we proceed north along Loop 1 and Farm-to-Market Route 1325 to Interstate Highway 35 and north beyond Georgetown, where we exit onto the Florence Highway (State Route 195). All along this route, we traverse or skirt the Edwards Aquifer and thus gain a dramatic perspective of the kinds of urban and suburban development that occur on this terrain. Just as to the south, along IH-35, one can foresee an eventual merger of a metropolitan complex that comprises Austin, Buda, Kyle, San Marcos, New Braunfels, Schertz, and San Antonio, one can also see the same process occurring more immediately to the north, where the boundaries between Austin and Round Rock are already indistinct and where Georgetown is rapidly extending out across what was ranch land only a short time ago. A remarkable case study of urban karst is presented by James Sansom, who recounts the discovery and initial exploration of Inner Space Caverns after the cave was penetrated by a geotechnical borehole during construction of IH-35.

Stop 4 allows a view of a karst terrain in the process of transformation: approximately 5,000 acres of rangeland are currently being developed into a new planned community, Del Webb's Sun City Georgetown. Here, Michael Thornhill will discuss hydrogeologic surveys conducted to assess local groundwater conditions and to ensure protection of groundwater as development proceeds. Issues here include not only protection of the Edwards Aquifer but also preservation of habitat for endangered species (cave-dwelling arthropods). During our tour of this property, we will visit a "blind cave" (one having no surface expression) that was discovered by means of geophysical techniques. Also, we will have lunch by a small karst void in the floodplain along Berry Creek, which under conditions of high water table issues forth as a major discharge site, but which is a locus of recharge during low stands of the subjacent water table.

Stop 5 is Lakeline Mall, a major commercial project on the Jollyville Plateau. There, development was delayed several years awaiting resolution of problems owing to the mall's occupying land that contains habitat for endangered cave-dwelling arthropods. Lee Sherrod recounts the issues that played out over a period of years and that involved the interface of karst geology, cave biology, economics, and politics. Described are attempts to monitor underground habitats in areas beyond the known extent of cavernous voids (those large enough to allow human access), and attempts to locate a suitable site for mitigation of lost habitat. Socioeconomic and political issues included the ups and downs of retail trade and the demand for shopping malls, engineering constraints, and the ever-changing regulations mandated by the Federal Endangered Species Act.

As we proceed from Lakeline Mall, we traverse the southern edge of the Jollyville Plateau, and we descend from this outlier of the once-contiguous Edwards Plateau into the deeply dissected terrain of the Bull Creek watershed. Near the edge of this karst upland we pass the 3M-Austin Center, a major industrial-research "campus center," which is built on the basal strata of the Edwards Limestone. As a "rolling stop" (Stop 6), we will discuss geotechnical investigations of this site as recounted by John Wooley, who notes a different kind of problem and a prescription for stable construction different from that prescribed for the intersection of LaCrosse Avenue and Loop 1-South.

From Stop 6, we descend the valley of West Bull Creek, and turning north onto Loop 360, follow the main course of Bull Creek and climb to the eastern edge of the watershed. There, along the drainage divide separating the Bull Creek and Shoal Creek watersheds is a densely developed suburb on the Edwards Limestone. Stop 7 visits a City preserve that contains a remarkable rimrock/shelter cave and spring complex along the margin of this plateau upland; nearby are caves containing Federally listed endangered cave species--all within a part of Northwest Austin that is developed as residential and commercial tracts. As we return to Loop 1-North via Spicewood Springs Road, we pass Spicewood Springs, which is recharged largely by urban runoff and whose water quality is thus threatened.

ACKNOWLEDGMENTS

We thank all the contributors to this volume. These people have brought diverse expertise to bear on urban karst, and in providing their expertise and vision, they point the way to possible solutions of local environmental problems. We thank Del Webb Corporation and National Wildflower Research Center for accommodating our visits on an extremely busy Saturday for both concerns. Special thanks are extended to Horizon Environmental Services, Inc., and specifically to Kim Lindros for taking charge in the production of this guidebook. Amanda R. Masterson provided editorial help for selected papers.

We extend hearty thanks to Robert Chipman for providing his fine field sketches of Lakeline Cave and to Charles Palmer for his help in ferreting out information on Austin Caverns and lime kilns in West Austin.

For general administrative support, we thank David A. Johns, President of Austin Geological Society. And for contributions to defray costs of refreshments for the field trip, we thank Groundwater Technology, Inc., R.W. Harden and Associates, Inc., and Robert S. Kier, Consulting Geologist.

C.M. Woodruff, Jr.
C. Lee Sherrod

Austin, Texas
March 1996

WEST ENFIELD/TARRYTOWN IS A KARST RECHARGE AREA--DOES ANYBODY CARE?

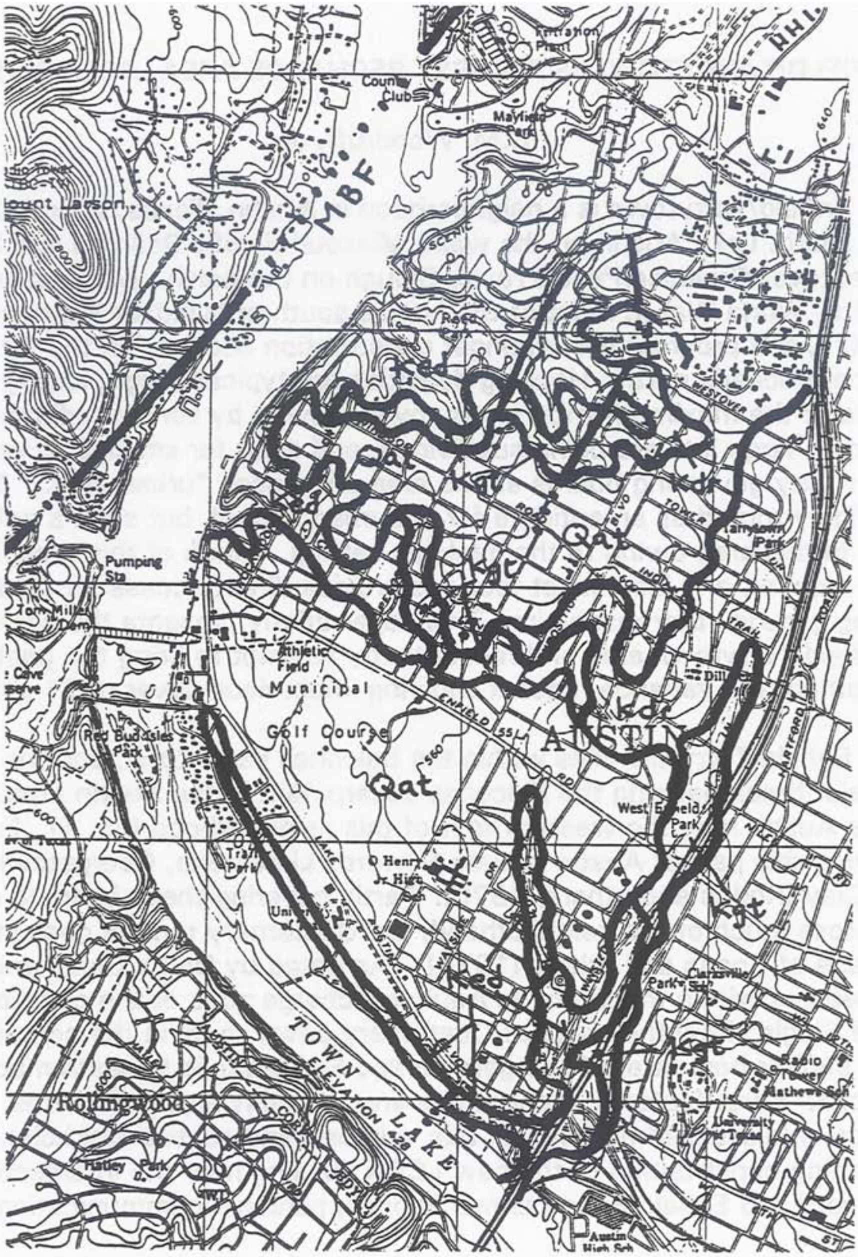
C.M. Woodruff, Jr.

West Enfield/Tarrytown is a neighborhood in Austin, Texas, bounded by Enfield Road on the south, Lake Austin on the west, Missouri Pacific Railroad and Loop 1 on the east, and Westover/Greenlee/Pecos/Taylor Slough on the north. Much of this area was developed after World War II; most of the homes south of Windsor Road were built during the late 1940's, and progressively younger construction occurred in the 1960's and 1970's as one proceeds north. Housing densities are typically high, locally greater than 8 houses per acre; the maximum impervious cover allowed by zoning ordinances is 45 percent. Today, large lots are being subdivided, and even for small lots, variances are obtained from City governing boards as the area undergoes "urban infill." This infill process is widely touted as an antidote for suburban sprawl, but such a policy is questionable in this area owing to the geologic setting. Much of this area lies atop part of the Edwards Aquifer, and local karst features provide direct access for urban runoff into the underlying groundwater reservoirs. This paper briefly presents the geologic setting of the West Enfield/Tarrytown area and recounts my attempt to bring the geologic setting to bear in opposition to a variance request allowing impervious cover of 51 percent.

West Enfield/Tarrytown lies within the Balcones Fault Zone, and the Mount Bonnell Fault, the major break defining the Balcones Escarpment in the Austin area, extends beneath Lake Austin near the western limit of this neighborhood (fig. 1). Faulted bedrock units underlying this part of Austin include Edwards Limestone, Georgetown Limestone, and Del Rio Clay (Rodda and others, 1970). Partly covering these bedrock units, and extending across much of the neighborhood, are Quaternary terrace deposits (mostly Asylum Terrace of Rodda and others [1970]). As noted by De La Garza and Slagle (1988), this entire area lies within the Edwards Aquifer recharge zone or the contributing zone. De La Garza and Slagle show the areas of Quaternary cover to be in the contributing zone, even though aquifer host strata (Georgetown and Edwards) lie beneath much of the various alluvial terraces. Karst features occur in this area, notably Austin Caverns, formerly a commercial cave (discussed by Reddell, this volume), and several sinkholes, including one discovered during construction of the new LCRA building near the intersection of Lake Austin Boulevard and Enfield Road (James Reddell, personal communication, 1996).

In 1994, I was a principal party involved in opposition to a variance request brought before the City of Austin Board of Adjustment. The variance requested an increase in impervious cover for a residential lot to 51 percent from the 45 percent allowed in this area. In my opposition to this variance, I noted that the neighborhood lies on the Edwards Aquifer and that karst features occur in the vicinity. I also noted that increased impervious cover increases flood hazards, and I pointed out that homes downgradient from the variance property were flooded during the 1981 Memorial Day Flood. With these facts, I presented a petition of several neighbors, who also opposed the variance. This case was considered shortly after enactment of the now-overruled SOS ordinance, which did not apply to this neighborhood, but which imposed a maximum impervious cover limitation for <u>commercial</u> development of 45 percent. Given these conditions, I was confident that the City Board Members would deny this variance request.

Notwithstanding my confidence, such variances are commonplace today, as the economic value of property in this part of Austin is very high. Hence, market pressures for



Explanation:

Quaternary surface deposits

Qat--Quaternary alluvium and terrace (undivided)

Cretaceous bedrock units

Kdr--Del Rio Clay

Kgt--Georgetown Formation

Ked--Edwards Limestone

Other features

--normal fault, dashed where inferred, dotted where covered (MBF = Mount Bonnell Fault)

Figure 1. Generalized geologic setting of West Austin (modified from Rodda and others [1970]).

overbuilding/ infilling is strong. Commonly, small houses on large lots are razed, and enormous houses (or even two houses) are allowed, thereby continuing the process of adding to the urban density of the area. A recent issue of the Austin Chronicle, often a journalistic champion of the Edwards Aquifer, featured a cover story that recounted earnest attempts of local citizens to densely develop close-in neighborhoods--in the face of roadblocks (?) imposed by City rules and regulations. One case study was in West Enfield/Tarrytown, yet no mention was made that the lot is situated on a karst recharge zone. Presumably, the geologic facts were not known. Education of the general public is a continuing professional concern of geologists having expertise on issues relevant to society.

Appearances before City governing boards do not provide suitable forums for public education. People speaking at such meetings are limited to a small audience and a 3-minute time slot, with no further avenues for presenting information unless requested by a board member (i.e. you cannot speak unless spoken to). It was my impression that the 5-member Board of Adjustment had an attitude of not wishing to be "confused by the facts." They showed scant interest in my disclosure that Tarrytown occupied part of the Edwards Aquifer. In response to my presentation showing the requested variance to have impervious cover 13 percent higher than commercial densities allowed under the SOS ordinance, Board Member Fred Ebner rejoined, "The SOS ordinance does not apply to Tarrytown." The variance was granted. But variances must be justified by a "hardship;" the putative hardship cited by the Board was that the claimant occupied a small lot!

In summary, there is a gap in our common knowledge and concern regarding "The Aquifer." Most public attention in Austin is accorded Barton Springs Segment of the aquifer, which is understandable given the popularity of Barton Springs. However, geologists familiar with bedrock and hydrologic conditions should try to increase public awareness of the fact that there are yet other environmentally sensitive areas in the city besides Barton Springs. Clearly, given the development pressure in West Enfield/Tarrytown and given its situation on a karst terrain, we may expect a long-term worsening of groundwater conditions and increasing flood hazards of densely developed areas.

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AUSTIN CAVERNS, TRAVIS COUNTY, TEXAS

James R. Reddell

Austin Caverns, presumably once one of Austin's environmental gems, serves as a classic example of the destruction of a valuable natural resource through neglect and irresponsible urbanization.

The earliest history of the cave is unknown. An 1840 reference in the Telegraph and Texas Register has been ascribed to the cave. This certainly is in error and the cave described there probably refers to Bandit Cave in Rollingwood.

It is unknown if Austin Caverns ever had a humanly accessible natural entrance. The first recorded entrance was in the wall of a quarry. Early references indicate that the cave was known prior to the quarrying operation but no reliable information has been found. In 1932, Frank Chote of Houston opened (or enlarged) an entrance in a large depression about 180 ft. north of the quarry entrance. A stairway and electric lights were installed and the cave was operated commercially. This venture failed after a few months, as did several other commercial caves in Texas during these difficult times. The cave was considered a hazard and at some point the sinkhole entrance was sealed. This entrance, however, re-opened a few years later.

The cave was mapped in 1941 by Carl Clayton. This map shows about 500 ft. of passage, including several rooms, the largest more than 50 ft. in diameter. The cave reportedly contained numerous attractive speleothems. In 1948 when the first description was published most of the speleothems were broken.

Two passages extended from the bottom of the 25 ft. deep entrance. One to the south extended about 180 ft. to an opening in the quarry wall. The other passage led north into a series of passages and chambers. The first systematic exploration of the cave for which there is reliable information was in 1952 by the University of Texas Speleological Society. At that time they found a large part of the cave blocked by collapse. Additional collapse occurred in 1953 and in 1954 the sinkhole entrance was again sealed. About 200 ft. of passage was still accessible from the quarry entrance until about 1959 when the quarry was filled and houses built on it.

The contemporary history of the cave began in 1963 when plans for development indicated the need for a storm sewer drain to prevent flooding of the depression in which the sinkhole entrance had been located. The old sealed entrance was re-opened and storm waters channeled into it by a drain. Unfortunately only a portion of the fill was removed and only the small southern section was available for direct entry by water. The first exploration by cave explorers of the cave revealed only about 30 ft. of passage. Flood waters entering the cave opened up the passage to the south to the sealed quarry entrance.

In recent years trash, leaves, and silt have blocked entry into the southern passage. As a result water is undermining the sinkhole fill to the north on which the street is built. Early in 1995 settling of the fill damaged the street. Rather than deal with the problem correctly the city simply placed metal sheets over the street. The only long-term solution to the problem will be to remove more of the fill to allow water to enter the main part of the cave. Failure to do this will result either in serious collapse of the street or complete sealing of the cave with resultant flooding of houses built in the depression in which the cave is located (William H. Russell, personal communication).

In addition to the obvious undesirability of channeling road and yard runoff with its load of pollutants into the aquifer, any endemic cavernicole fauna has been extirpated from the system. It is remotely possible that cave-adapted species still exist in the northern part of the cave. This is unlikely because of the intense urbanization above the cave. The high degree of impervious cover will have reduced water entering the system. In addition, what water does find its way underground will carry a heavy load of pesticides, herbicides, fertilizers, and other pollutants. This isolated limestone region doubtless contained an entire community of cavernicoles, many of which were probably limited to this small area and are almost certainly now extinct. Explorations prior to the most recent blockage of the cave found an incredibly repulsive passage containing every conceivable kind of trash and pollutants. The cave teemed with life, but the only species found were forms adapted for urban life (cockroaches, hot house millipedes, earthworms, pillbugs, etc.).

In summary, a large attractive cave potentially of great biological and geological interest has been converted into a source of direct pollution of the aquifer. Furthermore a failure to consider the consequences has already led to damage to the street and the potential for more serious problems is great.

THE EDWARDS AQUIFER IN THE TARRYTOWN AREA, AUSTIN

Raymond M. Slade, Jr.

BACKGROUND

The Tarrytown area of Austin incorporates a little more than a square mile in west central Austin. It is bound on the west by Lake Austin; on the north by 35th Street; on the east by Exposition Boulevard; and on the south by Enfield Road. Homes and businesses dominate the area, most of which was developed many years ago. About one-half of the Tarrytown area contains outcrops of the Edwards Limestone or Georgetown Limestone (Rodda and others, 1970); rocks that form the Edwards aquifer. These outcrops occur primarily in lower elevations along the creeks that drain the Tarrytown area.

OUTCROP GEOLOGY

The topography of the Tarrytown area defines the geology of its outcrops. Members 2 and 3 of the Edwards Limestone crop out in small areas near the mouth of a tributary to Lake Austin, at ground elevations less than about 510 feet just west of Reed Park. Member 4 encompasses the largest portion of the outcrop of Edwards rocks--it occurs at elevations between about 510 and 570 feet. The Georgetown Limestone, defined as the upper member of the Edwards aquifer, crops out at elevations between about 570 and 590 feet. At elevations exceeding about 590 feet, the Del Rio Clay or members of the Colorado River Terrace Deposits crop out.

WELLS

Less than a dozen wells in the Tarrytown area could be documented in reports of ground water in Travis county (George and others, 1941; Arnow, 1957; and Brune and Duffin, 1983). The earliest of these wells, completed prior to 1900 was used for livestock and irrigation. Most of the wells were drilled from 1939 to 1971. Their depths range from about 130 to 400 feet. The primary use for the wells has been domestic sources, including household supplies and swimming pools. It is unknown if any of the wells currently are in use.

GROUND-WATER LEVELS

Water levels were reviewed for 5 wells developed in the Edwards aquifer and within the Tarrytown area (Brune and Duffin, 1983; and Baker and others, 1986). The wells are scattered over the area, located from near the northern boundary of Tarrytown, to one located near it's southern boundary. The water-level elevations reveal a gradual gradient toward the south. Water elevations range from about 484 feet at the Austin State School to about 444 feet near the southern boundary. A review of the water-level variations reveal that the levels are more consistent closer to the southern boundary--the levels vary by about 9 feet in the northern part of Tarrytown and only by a couple of feet further south.

The elevation of Lake Austin on the west side of Tarrytown is fairly consistent at about 483 feet, while the elevation of Town Lake to the south is about 428 feet. There is a large difference in these elevations and the effect of these reservoir levels on the water levels in the Edwards aquifer is largely unknown. The elevation of Lake Austin apparently has little effect on Power House Springs--the spring's elevation of about 460 feet is about 23 feet lower than the elevation of Lake Austin.

SPRINGS

At least 2 springs have been documented in the Tarrytown area. Brune and Duffin (1983) report a spring at the confluence of small tributaries near Mayfield Park. A 1973 water-quality analysis of the spring indicates characteristics of water from the Edwards aquifer--it's inorganic-chemical content is dominated by bicarbonate. The spring is at an elevation of about 540 feet and reportedly discharged about 10 gallons per minute in 1973. This elevation, however, is considerably higher than water levels in wells in the aquifer, thus the spring probably represents a local flow system of water in lateral bedding planes above the normal water-table.

The other documented spring in the area is Power House or Dam Spring, located at Tom Miller Dam at an elevation of about 460 feet. Brune (1975) indicates the spring discharges through the Colorado River Terrace Deposits; Brune and Duffin indicate it to be an Edwards aquifer spring. An 1896 water quality analysis of the spring (Brune and Duffin, 1983), indicate it to display characteristics of water from the Edwards aquifer (bicarbonate concentration of 368 milligrams per liter). Five known discharge measurements have been made for this spring. Three measurements from 1895 to 1899 indicate the springflow to be 4.3, 10, and 8 cubic feet per second (cfs). The two measurements since then, however, in 1970 and 1973, indicate its flow to be 0.3 and 0.05 cfs, respectively. It is obvious that the discharge of this spring has diminished substantially with time--the cause for this reduction probably is unsubstantiated.

It is doubtful that the recharge area of the Edwards aquifer in the Tarrytown area could have accommodated the total discharge at Power House Spring. For example the Barton Springs portion of the Edwards aquifer produces only about 0.5 cfs per square mile of recharge area; the Rollingwood portion of the aquifer produces only about 1 cfs per square mile of recharge area to Cold or Deep Eddy Springs. The Tarrytown area covers only about one square mile, thus it is unlikely that this portion of the aquifer could have produced 8 or 10 cfs from Power House Springs. However, other water sources for the springs could originate from the Edwards aquifer north of Tarrytown or from water contained within the terrace deposits overlying the rocks of the Edwards aquifer.

DEEP EDDY SWIMMING POOL

Eilers Park and Deep Eddy Swimming Pool, Austin's first park, has been entertaining visitors since 1902. From 1902 until 1916, visitors swam in a deep hole near an eddy formed by a large rock in the bed of the Colorado River, and stayed at campsites in the 39-acre park. In 1916, the rock was destroyed and a concrete pool was built to accommodate swimmers--the pool is believed to be the first outdoor swimming pool in Texas. Three shallow wells, each about 24 feet deep, were dug about that time, and used to provide water to the flow-through pool. The ground elevation at the wells is about 450 feet and the water-level elevations for the wells is about 435 feet, based on measurements made in 1941.

There has been conjecture as to the source of water in the wells. Very little evidence could be found to verify the source. A chemical analysis of water from one of the wells, in 1954, indicate the water to be uncharacteristic of water from the Edwards aquifer. The bicarbonate concentration (161 milligrams per liter) and pH (8.2) are more indicative of water from the Colorado River or possibly from the terrace deposits prevalent in the area surrounding the wells.

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DISTRIBUTION OF SPECIFIC CAPACITY AND TRANSMISSIVITY IN THE EDWARDS AQUIFER

Robert E. Mace

INTRODUCTION

Karst aquifers are known for large variations in transmissivity, and the Edwards aquifer is no exception. Wells separated by only a few meters may have transmissivities that differ by several orders of magnitude. This heterogeneity results from a complicated network of solution-enhanced fractures and conduits. A well's productivity, therefore, depends on whether it intersects this highly permeable network.

Estimating transmissivity in karst aquifers can be conceptually difficult and limited. Flow in the aquifer may be turbulent, which might invalidate estimation methods that are based on laminar flow, such as those of Theis (1935) and Cooper and Jacob (1946). Large-scale vertical variability in hydraulic conductivity can also complicate the analysis of aquifer tests in the unconfined portion of karst aquifers (Eagon and Johe, 1972). Furthermore, because transmissivity in karst aquifers is scale dependent (Teutsch and Sauter, 1991; Rovey, 1994; Huntoon, in press), measurements on the scale of pumping tests may not apply to aquifer-scale modeling. Although these limitations must be considered, transmissivity can still be estimated and used in order to better understand karst aquifers. For example, many pumping tests in karst aquifers can be interpreted by means of standard techniques. Difficulties with vertical variability of hydraulic conductivity are reduced when drawdown in the unconfined zone is limited or when tests are run in the confined zone. Because transmissivities that are estimated from pumping tests sample aquifer heterogeneity, they are useful for water resources even if they might not apply at larger scales.

Although one would not rely solely on performance and pumping tests to characterize flow through a karst aquifer, knowledge of the distribution of transmissivity is useful for quantifying heterogeneity and investigating regional patterns of similarity in the aquifer. We analyzed the San Antonio segment of the Edwards aquifer, taking advantage of its large size, predominantly confined nature, and apparently wide range in productivity.

METHODS

We compiled transmissivity and specific capacity data, estimated transmissivity from specific capacity, and described the distribution of transmissivity. We obtained aquifer test data, including pumping and specific-capacity tests, from open-file records and research and technical reports. Because aquifer-test data were mostly specific-capacity tests, we estimated transmissivity using an empirical relationship between transmissivity, T [m^2 d^{-1}], and specific capacity, S_c [m^2 d^{-1}], for the Edwards aquifer (Hovorka and others, 1995; Mace, 1995, in preparation):

$$\boxed{T = 0.96(S_c)^{1.08}}$$

We described specific capacity and transmissivity using standard statistics of mean, median, and standard deviation and described them geostatistically using semivariograms (Clark, 1979).

RESULTS

We compiled 525 pumping and specific-capacity tests during this study. Specific capacity and transmissivity determined from these tests vary across eight orders of magnitude (10^{-2} to 10^{6} $m^2 d^{-1}$), an especially large range. They are approximately lognormally distributed (figure 1, we tested for significant deviation from normality using the Kolmogorov-Smirnov test). Table 1 summarizes means, standard deviations, and variances determined from lognormally transformed specific capacity and transmissivity values.

Mean transmissivity of the confined zone is more than 240 times greater than mean transmissivity in the unconfined recharge zone (table 1). A smaller saturated thickness in the unconfined zone accounts for only part of this difference, suggesting a real difference in permeability. However, lower permeabilities in the outcrop do not necessarily indicate less of an ability to transmit fluids–highly permeable zones in the outcrop might be saturated only during the wet season or immediately after rainfall.

Semivariograms show that specific capacity and transmissivity are spatially related on a regional scale. For example, semivariance of specific capacity and transmissivity decreases to a minimum as separation approaches zero, increases steadily during increasing separation, and then reaches and maintains a maximum value (figure 2). The semivariograms have large nuggets (large semivariances at a separation of zero). Although one possible cause of the large nuggets is measurement error, we think that the nugget represents near-well variability. Ranges of the semivariograms suggest that specific capacity and transmissivity are spatially related within 22 to 25 km (14 to 15.5 mi).

CONCLUSIONS

Specific capacity and transmissivity range across eight orders of magnitude in the San Antonio segment of the Edwards aquifer, and they are lognormally distributed. Variograms show that specific capacity and transmissivity are more similar to one another within 22 to 25 km (14 to 15.5 mi). A large nugget on the variograms could result from measurement errors and near-well-scale variability.

ACKNOWLEDGMENTS

This work was conducted as part of a study to characterize the regional permeability distribution of the Edwards aquifer for the Edwards Underground Water District. Erika Boghici and Norman Johns assisted with data collection and processing. Alan Dutton (Principal investigator), Susan Hovorka, and Eddie Collins provided insightful discussions and suggestions. Publication authorized by the Director, Bureau of Economic Geology, The University of Texas at Austin.

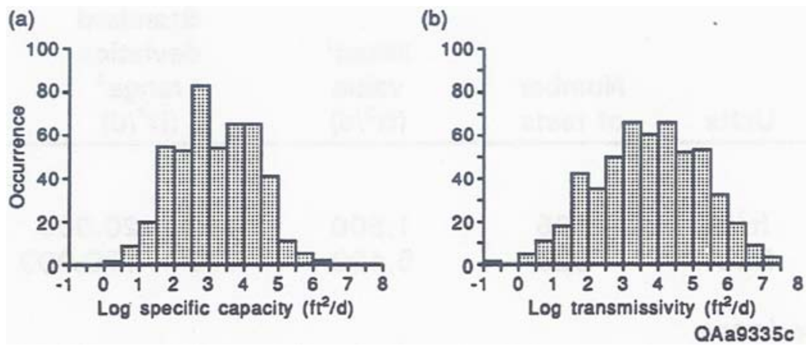

Figure 1. Histograms of (a) specific capacity and (b) transmissivity in the Edwards aquifer.

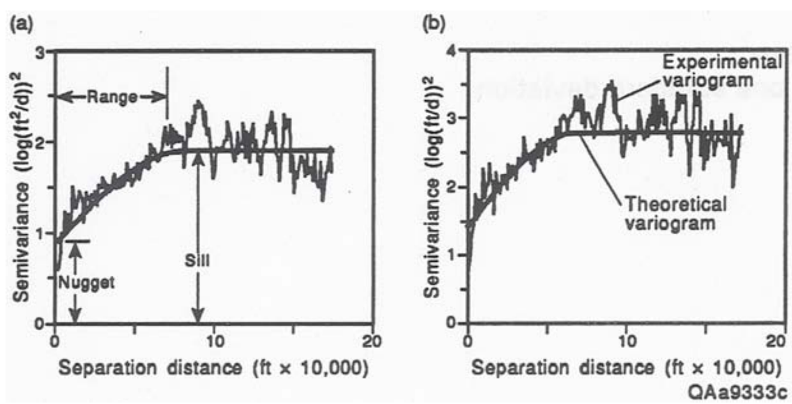

Figure 2. Semivariograms of (a) specific capacity and (b) transmissivity in the Edwards aquifer.

Table 1. Summary of specific capacity and transmissivity estimates in the Edwards aquifer

Variable	Units	Number of tests	Mean[1] value (ft^2/d)	Standard deviation range[2] (ft^2/d)	Variance $(\log[ft^2/d])^2$
All tests					
S_c	ft^2/d	525	1,500	110 - 20,000	1.27
T	ft^2/d	525	5,400	170 - 170,000	2.26
Tests in confined zone					
T	ft^2/d	399	18,000	720 - 460,000	1.97
Tests in unconfined zone					
T	ft^2/d	50	75	9 - 630	0.87

[1] Geometric mean
[2] Range of +/- one standard deviation

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PROTECTING THE EDWARDS AQUIFER AND ASSOCIATED KARST FEATURES DURING (AND AFTER) CONSTRUCTION OF THE NATIONAL WILDFLOWER RESEARCH CENTER FACILITY

Joshua Blumenfeld and David K. Northington, Ph.D.

"The hilly region is a vast line of cretaceous formation, extending from the Rio Grande, northeast, (through San Antonio and Austin), to the Red River...It yields everywhere an excellent limestone for building purposes."

Frederick Law Olmsted, A Journey Through Texas, 1857

The preservation and reestablishment of native wildflowers, grasses, trees, shrubs, and vines in planned landscapes is a tall order, one the National Wildflower Research Center has helped fill since its founding in 1982. Originally located in the fertile farmland along the Colorado River near Hornsby Bend in Southeast Austin, the Wildflower Center recently relocated to 42 acres of degraded ranchland in the Hill Country of Southwest Austin. This move was not only geographic, but geologic, and construction of the new Wildflower Center facility gave the Center an opportunity to practice the many concepts of environmentally conscious construction and natural resource conservation it has espoused since its inception. This was especially important since the Wildflower Center facility is constructed over the Edwards Aquifer; protection of the aquifer and its associated karst features was a primary objective. This paper examines the geologic setting of the National Wildflower Research Center and, in particular, the many steps taken before, during, and after construction to minimize impact to the karst terrain and protect two natural recharge features on site.

During the Cretaceous, about 100 million years ago, a shallow sea covered what we now call the Central Texas Hill Country (Spearing, 1992). Shells of marine organisms and carbonate mud were deposited, forming the Edwards Limestone that underlies much of Austin and the Wildflower Center (Hauwert, 1995; Rose, 1972; Spearing, 1992). The Gulf of Mexico retreated from Central Texas about 60 million years ago, and displacement along the Balcones Fault 15 to 20 million years ago uplifted the Edwards Plateau, allowing water to permeate the soluble limestone and dissolve the carbonate rock (Spearing, 1992). This weathering eventually created the Edwards Aquifer, which extends in a crescent shape east from Del Rio to San Marcos then north to Temple and beyond.

Southwest Austin comprises the middle portion of the Edwards Aquifer, named the "Barton Springs Segment" after the only major outflow of the aquifer in this area. Six creeks flow over the recharge zone of the Barton Springs Segment and contribute to the aquifer: Barton Creek, Williamson Creek, Bear Creek, Little Bear Creek, Slaughter Creek, and Onion Creek (Slade, et al., 1986).

Since the Edwards Aquifer is a karst aquifer, water flows freely through underground channels and does not have impurities filtered out. Waterborne pollutants carried by the creeks or by rain easily enters the aquifer through hundreds of caves, sinkholes, faults, and fractures in the Edwards Limestone. This knowledge was one of the driving forces in construction techniques used at the Wildflower Center.

When the Wildflower Center first acquired the land for the new facility in 1989, general opposition to construction anywhere over the Edwards Aquifer was quite vocal.

However, these concerns were quickly dispelled once people saw the care and extensive pre-planning that went into the layout and design of the facility before the first shovel of dirt was turned.

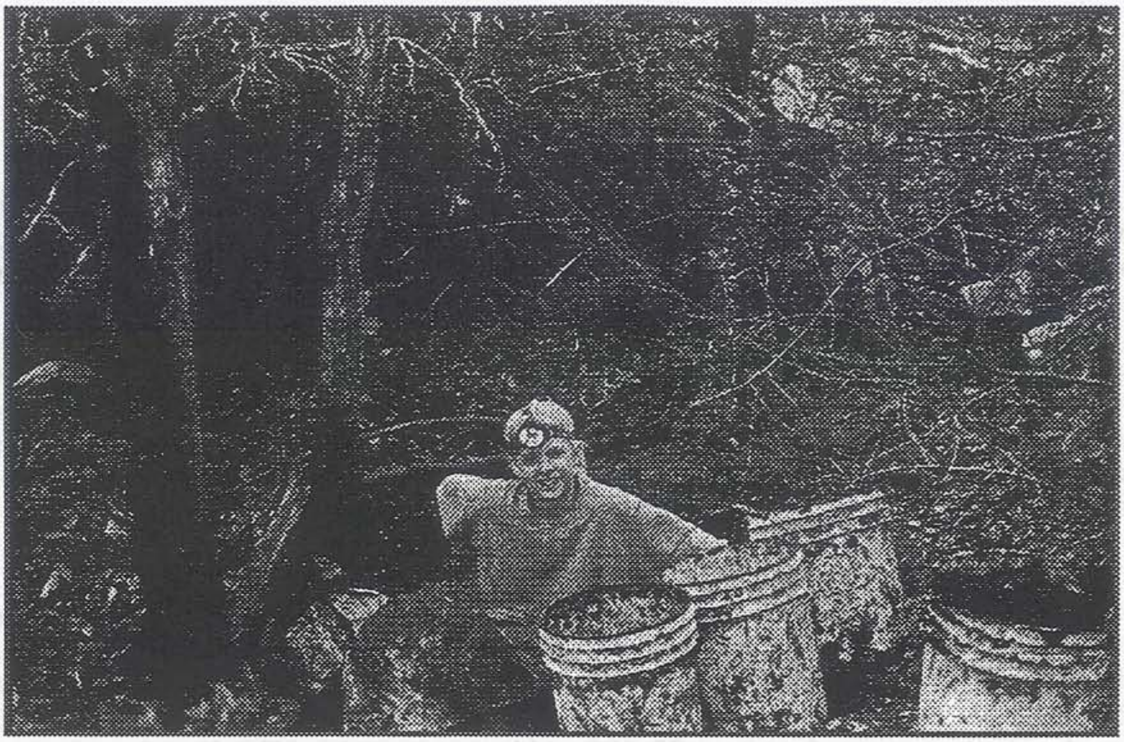
Soon after acquisition of the land, a formal site inventory was conducted to establish placement of Center buildings for maximum use of existing topography and protection of the aquifer. At this point, it was decided that a campus of separate buildings, rather than one large building, would lead to the greatest protection of natural resources on site. In addition, two karst features were identified: a small opening located in the middle of the Slaughter Creek watershed (in what is now part of the Wildflower Meadow behind the Visitors Gallery), and a larger cave just off what is now the Nature Trail (Woodruff, 1992).

The small karst opening is an 18 inch conduit leading directly into the Edwards Aquifer. During heavy rains, a whirlpool of water flows freely into the opening. The larger cave lies at the bottom of an approximately 25 foot closed depression surface sink surrounded by natural vegetation. According to Warton (1996), "The entrance drops vertically for 5.5 feet intersecting and opening onto a 'solutionally' enlarged bedding plane room containing numerous 'Spelothems' (Stalactites, Stalagmites, and Flowstones). The floor of this room is composed of loose rocks, soil, and sediments washed in from the surface over long periods of time. Present ceiling heights in this room range from...2.5 feet up to 5 feet...The cave exhibits evidence of moderate to strong capabilities for Point Recharge Loss, and is likely to be an 'Intermediate' Range Point Recharge Feature."

Like many larger karst features, this cave was used as a garbage dump by former owners of the land. Restoration and clean-up of this valuable resource was an important Wildflower Center activity during construction, and continues to be a major part of the Center's land management plan. The clean-up was supervised by Mark Sanders, of the City of Austin Nature Preserves, and Nico Hauwert, of the Barton Springs/Edwards Aquifer Conservation District, assisted by Marcia Hermann, the Wildflower Center's natural lands manager. Members of the University of Texas Speleological Society did most of the trash removal over four weekends (Figure 1). More than five truck loads of trash were removed, including boots, tires, bottles, barbed wire, and cans. While most of the refuse was carted away to the City of Austin landfill, some items were preserved for display in the Center's Visitors Gallery (Figure 1).

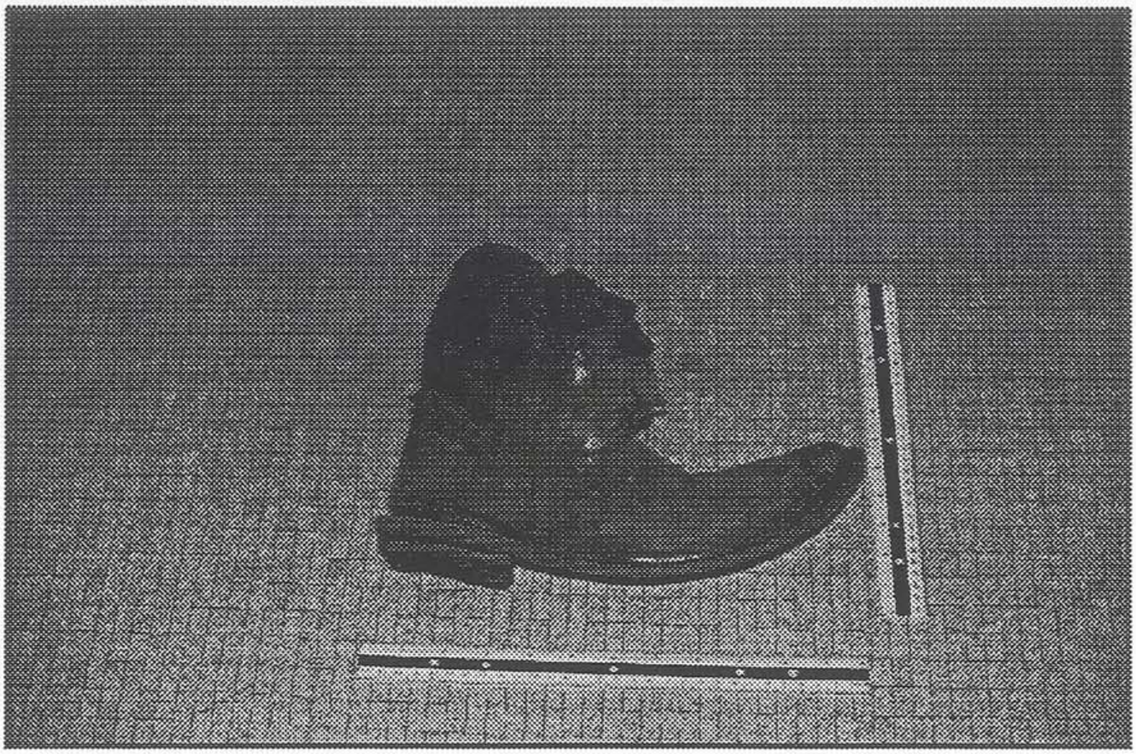
Due to the extensive pre-planning, site assessment, and design strategies to minimize environmental impact, construction began three years after site acquisition and proceeded concurrently with the cave clean up. Several design strategies and construction techniques were used to provide maximum protection to the two on-site karst features, particularly the early decision to use several buildings sited using natural topography rather than one large building which would have necessitated heavy cut and fill. This allowed most natural vegetation to remain in place and did not impact the natural watershed. In addition, construction traffic was restricted to narrow lanes and special sand pits were used to trap debris from cement truck hose-down.

To further protect the karst features, a berm made of felt, wire, and site-collected stone was erected just below the construction area and a second berm was placed totally around the smaller karst opening. These berms were required by the City of Austin, and are being removed as vegetative cover reaches 90 percent in the construction zones. The



A

Cleaning trash from Wildflower Cave, National Wildflower Research Center.



B

Example of debris removed (less photogenic - but more noxious - example included rusted, empty paint-thinner container).

FIGURE 1

Wildflower Center will continue to enhance the vegetation around the two karst features to improve the quality of water entering the Edwards Aquifer through vegetative filtration.

Protection of water entering the Edwards Aquifer is not limited to the areas surrounding the karst features. In fact, all water flowing through the Center or falling on the Center is either treated in a series of five sedimentation/filtration ponds or collected for re-use in a rooftop rainwater harvesting system (the largest of its kind in North America).

All run-off from impervious surfaces (parking lots, stone walkways, etc.) is diverted into one of five sedimentation/filtration ponds before it is allowed to run across open grassland and into the dry creek bed that channels water to the karst features. Water flows first into the sedimentation pond, where sediments sink to the bottom. The water then flows into a filtration pond filled with sand, which traps many smaller impurities. As needed, sand in this pond will be removed and replaced with fresh sand.

The Center collects rainwater from the roofs of all major buildings in a series of cisterns, where it is stored for use in the gardens and grounds. The clean draining tin roofs divert rainwater into one of three cisterns located around the Courtyard -- in fact, the Observation Tower is really a 10,000 gallon cistern which drains excess water into two 25,000 gallon storage tanks behind the Demonstration Gardens. Since the Edwards Aquifer provides drinking water for about 35,000 residents of southern Travis and northern Hays Counties, the Center's rainwater collection and use helps avoid depletion and contamination of this resource.

The Edwards Aquifer is recognized as the state's "most vulnerable groundwater supply" (Barton Springs/Edwards Aquifer Conservation District, 1994; Texas Water Commission, 1989). Preventing contamination and environmental impact to this irreplaceable resource becomes ever more imperative as Austin continues its rapid growth and expansion. The National Wildflower Research Center has convincingly demonstrated that it is possible to balance environmental protection with large-scale construction in a way that is not only aesthetically pleasing, but protects and enhances the natural resources already on a site.

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GEOTECHNICAL ENGINEERING IN KARST TERRAIN--
CASE HISTORIES IN THE EDWARDS LIMESTONE

John A. Wooley, P.E.

The practice of geotechnical engineering in central Texas and the greater Austin Metropolitan area is challenging because the area is blessed, or cursed, with a wide variety of ground conditions ranging from unconsolidated soils associated with the Colorado River to hard massive limestones of Cretaceous age. Perhaps the most challenging ground condition, with the arguable exception of the highly expansive stiff to hard fissured clays and clay-shales predominant in the area, are those that result from karst limestone, most notably the Edwards Limestone. The author would characterize (in engineering terms) the Edwards Limestone as quite variable with constituent materials consisting of at least the following: hard massive limestone, soft weathered limestone, relatively hard dolomite, soft weathered dolomite, soft to hard clay-filled voids, fractured or broken limestone rubble mixed with clay, and open voids - possibly fully or partially filled with groundwater. Of course, combinations of any of these subsurface conditions might be present on any project situated on the outcropping Edwards Limestone, as the most notable expectation of the formation is its unpredictability. Accordingly, the prudent Geotechnical Engineer will approach engineered facilities in the formation with caution, and the presumption that wide subsurface variability exists. Foremost in the realm of the unpredictable are the presence of solution voids, cavities, caves and the like, and resultant solution collapse zones. Experience suggests that subsurface anomalies are more predominant near and along faults, fractures, lineaments and the like. Most significant solution activity has been noted by this author to be oriented in a horizontal or lenticular fashion along predominant bedding planes, and often accentuated by easy access to groundwater through vertical joints.

Unfortunately, modern tools for quantifying subsurface variability are not much more advanced than they were 50 years ago. Yes, geophysical tools are available: Ground Penetrating Radar, Surface Seismic, Shallow Seismic Profiling, and Resistivity Studies. The author has found these tools mostly unreliable in that they 1) do not offer fine enough resolution, 2) are not reproducible, 3) have variable success ratios depending on factors that are apparently site specific, 4) are too costly for most commercial projects and, 5) may be time-consuming relative to most fast paced schedules of recent years. Accordingly, the common tools of the Geotechnical Engineer working in the Edwards Limestone is a wet rotary drill rig with conventional, or wireline NX-sized core barrel. Foundation borings are commonly drilled at about 100 ft spacings to depths of 25 to 40 ft depending on column loads, and finished elevations of structures in question. The driller's log, including most importantly notes regarding drilling fluid loss, Kelley drop, and drill chatter, together with calculations of Recovery and Rock Quality Designation[1] (RQD) are the tools available to the Geotechnical Engineer for ferreting out subsurface karst anomalies. (The RQD is defined as the total length of core pieces 4 inches long or longer divided by the total core run length.) A prudent Geotechnical Engineer will try to access all available geologic information on a particular site. Of particular value is data pertaining to structural lineations or karst features mapped by a practicing Geologist. Unfortunately, on most projects, such data is not readily available.

1 Deere, D.U. (1968) "Geological Considerations," Chap. 1 in K.G. Stagg and O.C. Zienkiewicz, Rock Mechanics in Engineering Practice, New York, Wiley, pp.1-20.

The principal engineered facilities upon which karst features may have a profound effect include the following:

Structural Foundations, Deep and Shallow;
Utility Excavations;
Tunnels;
Pavements; and
Cut Slopes

Each type of facility, and the potential impact of karst features on each will be discussed in the paragraphs that follow. Subsequently, several case histories will be presented that recount how karst features have impacted either the design, or construction, of an engineered facility of the types described.

STRUCTURAL FOUNDATIONS

Structural loads are typically carried to the subsurface through footings. These footings are generally selected as one of two types: shallow or deep. Shallow footings are typically described as spread or continuous footings. Deep footings are typically referred to as drilled piers, drilled shafts, or drilled caissons and in limestones are typically drilled in place with large, high-powered mechanical augers and are filled with cast-in-place reinforced concrete.

Shallow spread footings are typically sized based on an allowable bearing, or contact, pressure. In rock, these contact pressures are generally selected as a function of the unconfined compressive strength of the rock mass, and the Geotechnical Engineer's impression of the overall rock quality. Obviously, the selection of a shallow spread footing, founded 2 to 3 ft below grade, would not be an ideal foundation type if there were an open lenticular void system located at a depth of 4 ft below grade (see Figure 1). Consequently, the driller's log and RQD values obtained from the field investigation begin to play an important role in the Geotechnical Engineer's evaluation of shallow footing alternatives.

Because evaluation of potential voids in karst limestones is difficult, and because the possibility that solution caves or caverns exist that were not identified during the investigation, many Geotechnical Engineers believe the best foundation system for a karst limestone is a deep drilled pier (shaft, caisson). The reason for this is that drilled piers are customarily designed to support structural loads not only on the basis of an allowable end bearing pressure, but also allowing for a component of side friction acting between the pier side and rock socket (See Figure 2).

It is common practice that some Geotechnical Engineers will specify probe holes to be extended beneath the bottoms of shallow footings or drilled piers to determine the potential presence of voids beneath the foundation element. If this practice is employed, the probe hole is usually taken to a depth of about one spread footing width, or 1.5 to 2 drilled pier diameters below the planned footing bottom. The use of probe holes is entirely discretionary and generally depends on the level of the Geotechnical Engineer's uncertainty, with regard to subsurface conditions, and on the conservatism of the actual design parameters he has recommended. Should probe holes reveal voids of significance to the Geotechnical Engineer's design, drilled piers offer an advantage, as it is easier to return a high-powered drill rig to the pier hole than it is to maneuver hoe rams, rock saws,

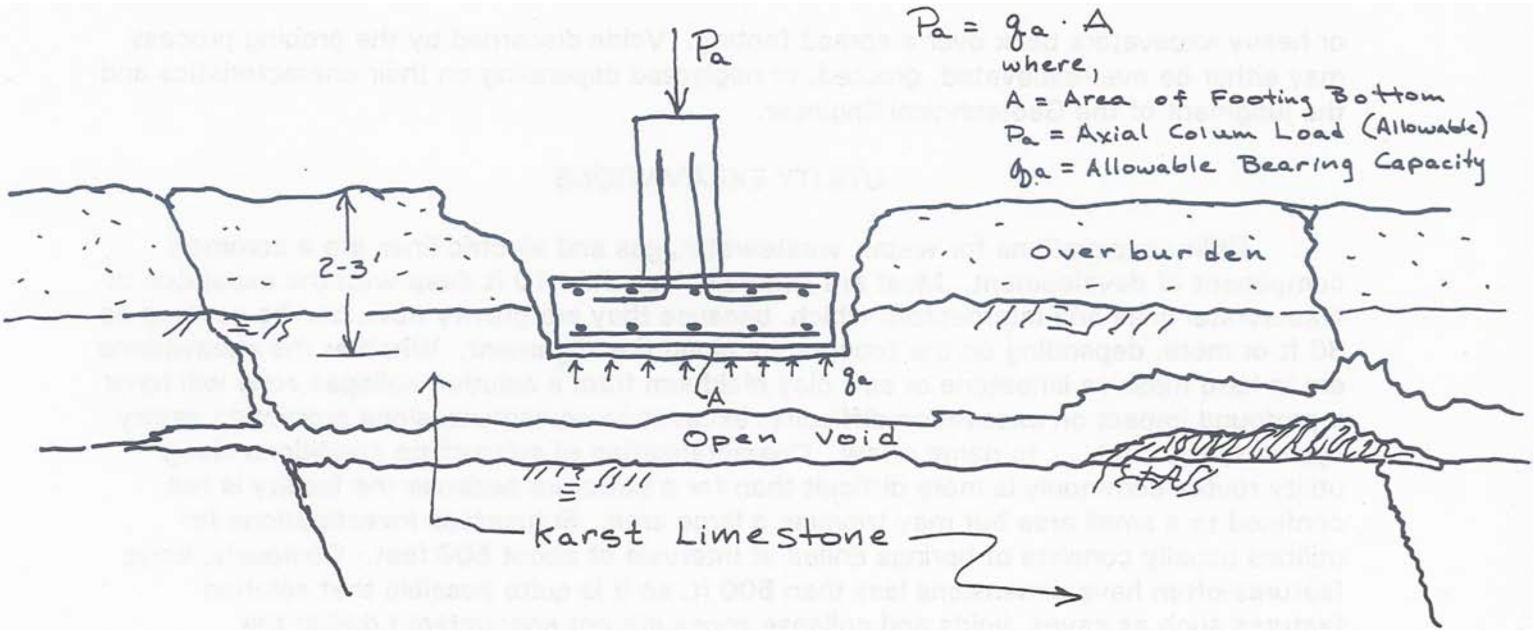

Figure 1: Shallow Spread Footing Over Lenticular Void

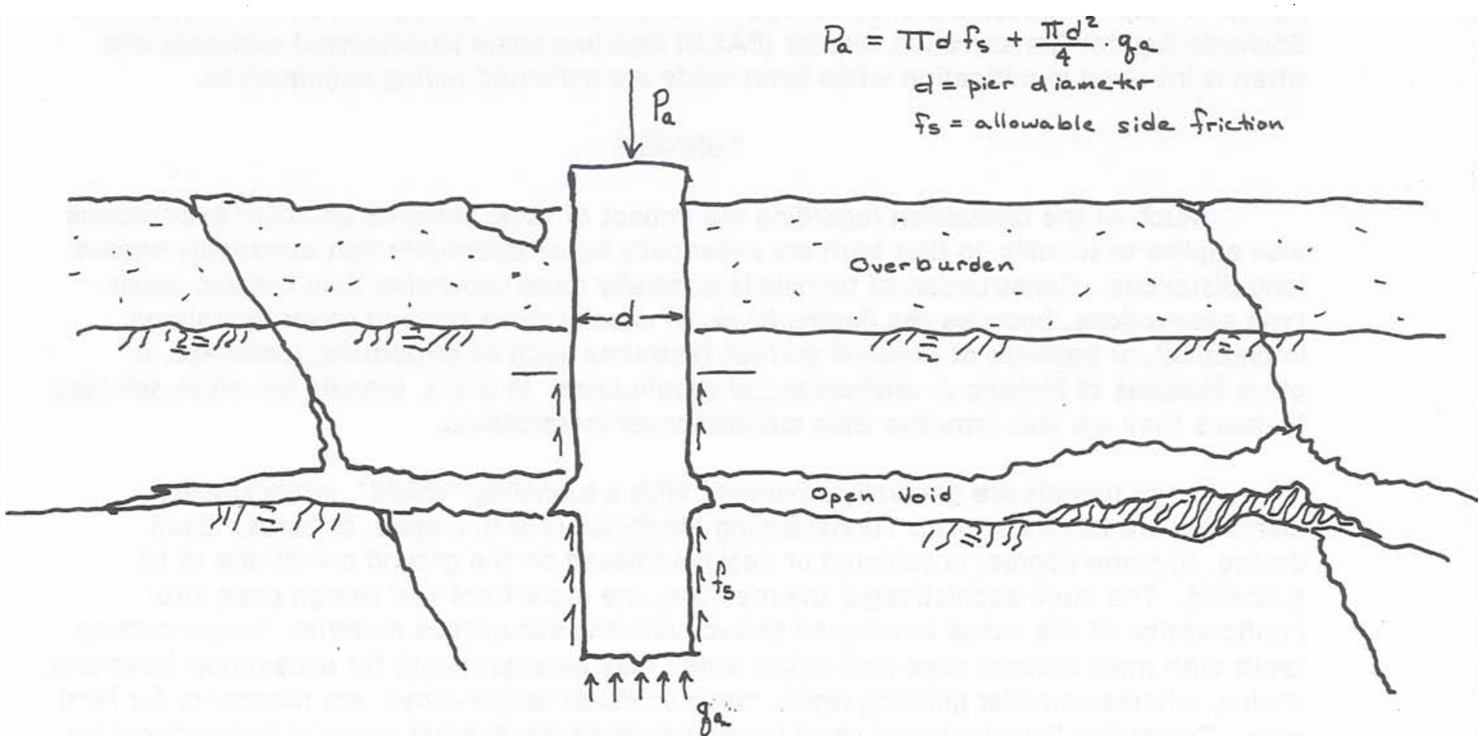

Figure 2: Drilled Pier In Lenticular Voids

or heavy excavators back over a spread footing. Voids discerned by the probing process may either be over-excavated, grouted, or neglected depending on their characteristics and the judgment of the Geotechnical Engineer.

UTILITY EXCAVATIONS

Utility excavations for water, wastewater, gas and electric lines are a common component of development. Most are generally less than 10 ft deep with the exception of wastewater lines and interceptors which, because they are gravity flow, can be as deep as 30 ft or more, depending on the topography along the alignment. Whether the excavations are in hard massive limestone or soft clay residuum from a solution collapse zone will have a profound impact on excavation difficulty, excavation equipment, slope protection safety systems, and cost .... to name a few. Characterization of subsurface conditions along utility routes commonly is more difficult than for a structure because the facility is not confined to a small area but may traverse a large area. Subsurface investigations for utilities usually consists of borings drilled at intervals of about 500 feet. Obviously, karst features often have dimensions less than 500 ft, so it is quite possible that solution features such as caves, voids and collapse zones are not encountered during the geotechnical investigation. Accordingly, project specifications must put the contractor on notice that changes of conditions are possible. Unfortunately, the contractor with the lowest bid might not invest adequately in contingencies for dealing with acceptable changes in subsurface conditions, and often his (her) only remedy is through a claim to the owner for a change of conditions during construction.

In the recharge zone of the Edwards aquifer, developers are required to submit a Water Pollution Abatement Plan (WPAP) to the Texas Natural Resources Conservation Commission, (TNRCC), which would include possible methods to mitigate damage to the aquifer if voids or caves are encountered in the subsurface. In addition to the TNRCC, the Edwards Aquifer Conservation District (EACD) also has some jurisdictional authority and often is involved in mitigation when karst voids are exhumed during construction.

TUNNELS

Much of the discussion regarding the impact of karst features on utility excavations also applies to tunnels, in that both are essentially linear structures that commonly extend long distances. Construction of tunnels is generally more expensive than cut and cover type excavations, because the depths involved usually make cut and cover operations impractical, or because of physical surface restraints such as structures, roadways, or other features of historic or environmental significance. In short, tunnels are often selected because they are less intrusive than cut and cover installations.

Large tunnels are generally advanced with a tunneling "shield", while smaller diameters are advanced with Tunnel Boring Machines (TBM), augers, or bores. Each device, to some degree, is selected or designed based on the ground conditions to be tunneled. The more sophisticated the machine, the more front-end design goes into configuration of the cutter head used to excavate the subsurface material. Larger cutting teeth with more surface area (and softer steel) may be appropriate for excavating clays and shales, whereas smaller grinding teeth, made of much harder alloys, are necessary for hard rock. Crystalline limestone and chert layers are often the hardest material encountered by tunneling devices.

The high variability of the Edwards Limestone presents great challenge for the tunneling contractor. In faulted and solution prone areas the contractor might be tunneling in hard crystalline limestone, nodular chert, soft soil in-filled in solution zones, mixed soil and limestone boulders in a collapse zone, running or caving soils and flowing groundwater in solution zones, and mixed-face conditions where the tunneled cross section includes a combination of these. All of these possibilities make tunneling in the Edwards Limestone a significant technical challenge and make the geotechnical investigation even more important. Investigative borings spaced closer than 500 ft are encouraged, as well as a thorough geologic assessment, including use of any geophysical tools that might be available.

PAVEMENTS

As with utilities and tunnels, pavements are linear and subject to ground condition variability over a large area. While the other linear facilities are subject to fairly deep variability of subsurface conditions, pavement designs are generally based on soil and rock conditions in the upper 1-2 ft of the subsurface, unless grade changes require cut or fill operations. Nonetheless, subgrade conditions may change dramatically from hard weathered limestone to soft fat clay over a very short distance in a karst environment (example: solution collapse zones).

Because of the potential subsurface variability in the Edwards Limestone, most pavement designs are presented with two different thicknesses of flexible base material: one for a weathered limestone subgrade, and one for a fat clay subgrade. Depending on projected traffic loadings on the pavements, the differences in flexible base thickness may be as little as 3 inches or as great as 10 inches. The determination of which thickness to use is generally made by the designing Civil Engineer by picking the more conservative thickness, but the actual thickness used could be changed in the field once the pavement subgrade rough cut has been made. Literally thousands of dollars could be saved on most projects if the cut subgrade is limestone rather than residual clay. In general, the presence of voids beneath the subgrade is not considered in design as any void of consequence to the light load of the pavement would likely be discovered during construction by heavy construction traffic, or by utility excavation.

SLOPES

Just as the competency of the possible constituents of the Edwards Limestone varies, so varies its ability to maintain stable slopes. The most massive rock of the Edwards Limestone could maintain effectively vertical slopes, subject of course to the judgment of the Geotechnical Engineer and predicated on his expectations of variability, faulting, fracture patterns and the like. The softest of clay soil residuum or material within clay-filled voids or solution collapse zones, depending on its thickness and proximity to groundwater, may not be stable on slopes as flat as 1H:1V. Mixtures of hard clay and weathered limestone ledges might be stable on a slope of 0.5H:1V.

Once again, the problem facing the Geotechnical Engineer and Civil Engineer is the inability to predict with dependability what the actual conditions might be at the time of excavation. In the example of a roadway, the deeper the cut and the flatter the slope, the more land or lot size is lost to the slope or slope easement, the less useable lot space remains, with less value to a prospective purchaser. Accordingly, the Geotechnical

Engineer must try to evaluate the variability of subsurface conditions as best he can yet temper his recommendations with the warranted conservatism while at the same time recognizing cost and value considerations.

CASE HISTORIES

The following case histories fall generally into several of the categories identified previously. Specifically these are: foundations, utility excavations, pavements, and slopes. A map showing the locations of the various case histories is presented as Figure 3.

Case History 1: Austin Center 3M Foundations. The campus of the Austin Center 3M complex is located on outcropping Edwards Limestone atop the Jollyville Plateau. The phase I construction was designed in 1984 by a Houston-based Architectural Engineering firm. The foundation system was to be supported by shallow spread footings. The geotechnical investigation had allowed either shallow spread footings or drilled piers. Plans and specifications called for the shallow spread footings to be probed with percussion drills to a depth equal to the footing width, in order to determine the possible presence of voids beneath the footings.

In 1986, after the mass excavation established finished working subgrade elevations, the General Contractor used large rock saws to excavate around the perimeter of each individual spread footing, most of which were about 5 to 8 ft square and were designed using an allowable bearing pressure (q_a) of 20 kips per sq ft (ksf). After the perimeter excavation, hydraulic hoe rams were used to chip and excavate the hard rock from the centers of the spread footing excavation. Finally, probe holes were drilled from the bottom of the footing excavations. During the probing process a series of lenticular karst voids were discovered. These included both open, and partially clay-filled voids 8 to 12 inches thick. The system of voids were close enough to footing bottom and widespread enough to result in additional mitigative efforts. These included injection of a soil cement mixture into some of the smaller voids, and over-excavation of footings to greater depths where the voids were considered too large. In all, about 15 to 20% of the footings required some sort of mitigative measures to provide adequate bearing. Review of boring logs taken before construction provided only a hint as to actual difficulties, and this was only recognized in retrospect through low Recovery and RQD values and drillers' notes related to loss of circulation of drill fluid.

Subsequent to the construction of Phase I, the Phase 2a expansion and parking garage expansion have both been designed using drilled piers for support of column loads. Probe holes were also specified to investigate the presence of voids beneath the drilled pier bottoms. Use of drilled piers in karst limestone offers the ability to quickly deepen the pier if voids are encountered. Also, the structural capacity of the pier is developed through a combination of both end bearing and friction. The frictional capacity can be easily verified by observations of the condition of the side of the shaft as the pier is advanced.

Case History 2: McNeil High School Foundation. The construction of foundations for the McNeil High School in the Round Rock School District resulted in the use of a fairly


Case History 2
Case History 1
Austin
Case History 3
Case History 4
© 1995 DeLorme

Figure 3

innovative ground improvement technique for karst limestones[2], in this case the Edwards Limestone. Several cave openings were located on and immediately adjacent to the school property. After initial rock borings indicated the solution and cavity zone extended deeper than the 25 ft depth planned for the borings, the investigative depth was extended to 50 feet. In all, 9 of the 19 borings (47%) encountered cavities and caves extending as deep as 50 feet. The largest cave encountered was 5.5 ft in height.

Because the cavities extended to such a great depth, and because of the notorious hardness of the formation, the Geotechnical Engineer felt it would be more practical, and less expensive to try to grout the voids rather than drill and case through them and place concrete. Therefore, the foundation was designed to be supported by shallow spread footings. Probe holes were required for the spread footings, and it was decided to drill these first, case them with small PVC access pipes, analyze the probing program, and then proceed with a grouting program through the access pipes.

A total of 577 probe holes were drilled for the 577 footing locations with an air rotary drill. The drilling operation was carefully observed for cuttings, air circulation (blowback) and return in adjacent holes, as well as action of the drill and audible drill chatter. Results of the probing revealed the site to be more cavernous than originally thought. Cavities were found in 352 of the 577 holes (61%). After completion of the probing program, six 24-in. diameter access shafts were drilled into the cavernous areas. One cavern, so accessed, was found to be about 20ft-by-30ft-by-6ft tall. Many of the cavities were lenticular and interconnected with "arms" of variable size and shape.

Because of the sizeable volume of the elaborate labyrinth of cavities, an enormous volume of grout would be required to fill the voids. At this time the concept of " low slump grout columns" was conceived. This concept was to pump a low slump grout into the cavities and have it mound up to the ceiling. The column would not be used to transfer footing load but only to hold up the ceiling and roof of the cave or cavity. The logs of probe holes were examined and three conditions for grouting were determined: 1) grout with high slump grout those probe holes with no, or little, indication of voids, 2) grout with low slump grout those probe holes with obviously large voids, and 3) all other probe holes were grouted first with high slump grout to a capacity of one cubic yard, then the grouting operation was completed with low slump grout. This last procedure was used for probe holes that encountered small to medium sized voids (less than one foot thick).

Halliburton was contracted to provide both the low slump and high slump grouts which were specified to have 500 psi compressive strength at 7 days, and to have a maximum shrinkage of 0.75%. The low slump grout was also required to mound at least 10 ft tall with a base diameter of 10 ft or less. After three mix designs failed this latter criteria, Halliburton suggested treatment of the high slump grout with a chemical additive, Liquid Econolite, a sodium silicate solution developed by Halliburton for sealing porous zones in oil wells. A trial was conducted in the larger caves with personnel actually in the cave monitoring the effectiveness of the process. On the strength of these trials, the solution to the low slump grout problem was found by adding the Liquid Econolite to the high slump grout at a rate of 0.5 to 2.0 gallons per sack of cement. The high slump grout thickened within seconds of contact with the Econolite. The Econolite was injected into

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[2] Gunter, John A., P.E., Construction of Grout Columns in Cavities in the Edwards Limestone, Presented at the ASCE Texas Section Spring Meeting, Fort Worth, Texas, April 1987.

the high slump grout line at a high pressure (up to 300 psi) and the resulting mixture was then injected into the cavity, until a steady back pressure of 50 psi could be achieved, giving confidence that most voids of significance were mitigated.

The high-slump-modified-grout using Econolite offered several advantages over a completely separate low slump grout in that the same mixing equipment and batching procedures could be used throughout, and the resulting low slump grout was much stiffer and resulted in steeper grout columns having smaller bases and thus less volume. In all, 254 cu yds of high slump grout and 323 cu yds of low slump grout were consumed. The cost of the grouting program was about $150,000, which is much less than the original grouting program had been estimated to cost.

Case History 3: LaCrosse Avenue Cave in Utility Excavation. A sizable cave was encountered during installation of a subsurface utility (8-in. wastewater line) at the intersection of LaCrosse Avenue and Dahlgreen Lane at the Circle C Ranch. The site is again within the Edwards Limestone. The utility excavation, which was about 3 ft wide and 3 ft deep, was being advanced in a northerly direction across LaCrosse Avenue in early 1992 while LaCrosse Avenue was under construction. The excavator punched through the roof of the cave at the approximate location shown on Figure 4. Two important issues facing the Developer were: 1) how to mitigate the presence of the cave beneath the intersection, and 2) what effect might the cave and associated smaller cavities have on the pavement beyond the immediate cave area. These issues were addressed by drilling 5 borings in the area around the known cave and by entering and mapping the cave itself.

The cave was found to be about 20 to 25 ft wide with a height of up to 5 ft at the location of the utility excavation. A plan view of the cave extent with approximate figures showing the height of cave and thickness of roof is presented as Figure 5.

After evaluation of the situation, and consulting with the TNRCC and EACD, the cave was mitigated by the following: 1) over-excavation of the cave portal to about 20 ft by 20 ft, 2) removal of soft soil and debris from the cave bottom, 3) backfill of the cave with open graded crushed limestone and ballast rock (to allow unperturbed air and water flow), 4) placement of a filter fabric above the rock backfill at a depth of about 2 ft, 5) placement of a reinforced concrete slab with dowel rods drilled and grouted into the competent rock in the cave roof, and 6) placement of crushed limestone base and hot mix asphaltic concrete pavement.

With regard to the impact of the cave network on other portions of the pavement in the area, it was determined that, although the cave, or a solution collapse feature, could be inferred in 5 of the 6 borings, the thickness and competence of the limestone roof above the cave zone, combined with the characteristics of the in-filled material, was adequate enough to provide satisfactory support for a relatively lightly loaded roadway of the type planned.

Case History 4: LaCrosse Avenue Slope Stability. The last case history presented is just a little east of Case History 3, still in the Edwards Limestone. The design of the extension of LaCrosse Avenue to South Mopac required a cut of up to 14 feet. One boring was drilled to investigate the deepest portion of the cut near the north side of the cut. The boring revealed residual soil and moderately weathered limestone to a depth of 5 ft, and

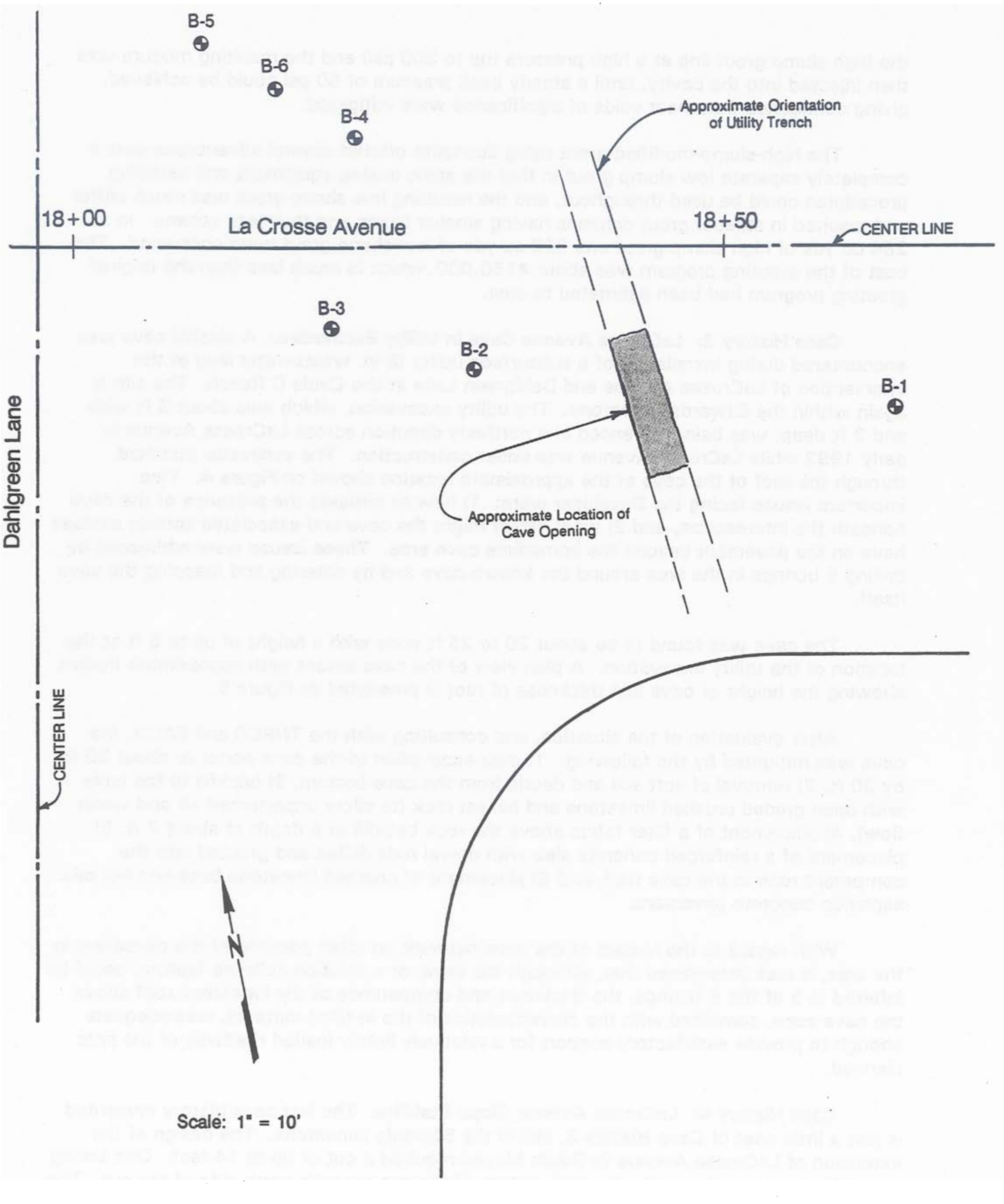


Figure 4: Plan Of Borings, La Crosse Avenue At Dahlgreen Lane

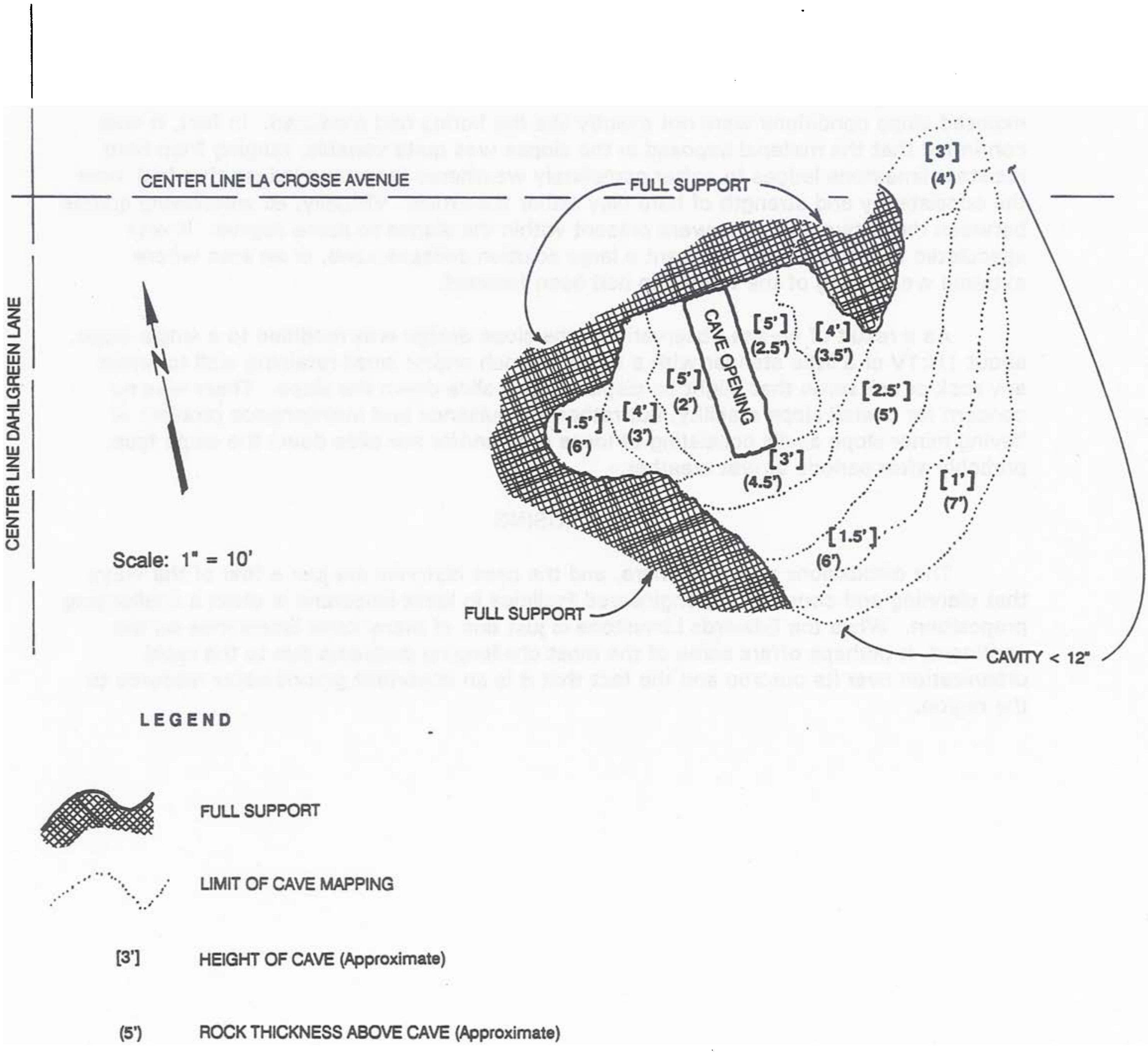


Figure 5: Approximate Cave Shape And Dimensions, Lacrosse Avenue At Dahlgreen Lane

variations of hard to soft limestone with clay seams and possible small solution seams below that depth. Based on these subsurface conditions, it was recommended that the top 5 ft (soils and weak weathered limestone) be sloped 1H:1V and below that depth (more competent rock) be sloped at 0.5H:1V, with a 3 to 5 ft wide horizontal bench at the transition point.

When the Contractor made his initial cuts, the Geotechnical Engineer was called to review the exposed conditions. After site reconnaissance, it was clear that the actual exposed slope conditions were not exactly like the boring had predicted. In fact, it was confirmed that the material exposed in the slopes was quite variable, ranging from hard resistant limestone ledges to softer completely weathered limestone ledges that had more the consistency and strength of hard clay rather than rock. Virtually, all weathering grades between these two extremes were present within the slopes to some degree. It was speculated that this might represent a large solution collapse zone, or an area where extreme weathering of the formation had been focused.

As a result of on-site observations, the slope design was modified to a single slope, about 1H:1V or a little steeper with a bottom bench and/or small retaining wall to arrest any rock or soil scree that might be displaced and slide down the slope. There was no concern for overall slope stability, but rather the nuisance and maintenance problem of having minor slope spalls consisting of loose rock and/or soil slide down the slope face, probably after periods of wet weather.

CLOSING

The discussions presented here, and the case histories are just a few of the ways that planning and constructing engineered facilities in karst limestone is often a challenging proposition. While the Edwards Limestone is just one of many karst limestones on the continent, it perhaps offers some of the most challenging problems due to the rapid urbanization over its outcrop and the fact that it is an important groundwater resource to the region.

THE DISCOVERY OF INNER SPACE CAVERNS

James W. Sansom, Jr.

Famous last words, "Take care for you might encounter some caves while drilling this location."

James W. Sansom, Jr.

In the spring of 1963 when I was employed as the Geologist for the Bridge Division of the Texas Highway Department (THD), one of THD's Core Drill Crews drilled into a large cavern south of Georgetown, Texas. My responsibilities as geologist included providing a geological perspective of the foundation conditions at proposed bridge sites to design engineers. This work entailed coordinating core drilling exploration, the overseeing of the quality of logging data from core holes, and geotechnical testing.

THD District 14 Headquarters located in Austin, Texas, had requested a drill rig to begin exploration core drilling for the bridges and overpasses for the Interstate Highway 35 bypass of the City of Georgetown. Upon my examination of their proposed route, the first overpass south of Georgetown would cross the Balcones Fault Zone. It would go over a frontage road and the Georgetown Railroad tracks. When I talked to Sylvan Turner, Core Driller, I suggested that he be cautious in drilling this site because he might encounter some voids and caves. This procedure consists of the drillers having to maintain tension on the steel cable that raises and lowers the drill kelly on his rig. If slack in the cable is not maintained, the drill bit will drop suddenly when a void is encountered and will sometimes cause damage to the bit or it can get stuck in the hole. Sylvan, being one of many drillers for whom I had worked in the summers while attending the University of Texas in pursuit of my Geology degree, didn't take me seriously. I was a young green-behind-the-ears geologist and what does a 'college boy' like me know about anything! As it turns out, I was fortunate to work during the summers as an assistant core driller for core drillers that taught me much about life.

Sylvan Turner obviously did not listen to me. When I heard about his having drilled into a large cavern, he had already lost a 10-foot section of his drill pipe with an attached 6-inch-diameter roller rock bit. His bit had dropped approximately 25 feet from where he drilled into the roof of the cavern to the floor of a large room. His bit had broken through some flowstone where it locked up. He was not able to recover it and ultimately twisted it off. He maintained correct tension on his kelly cable following this experience because he drilled several additional holes into the same large room, which is now called Outer Cathedral by the Inner Space Cavern owners.

Upon completion of the core drilling, a 24-inch-diameter hole was drilled into the cavern so THD personnel could map the extent and conditions of the cavern relative to foundations for the planned overpass. The 24-inch hole was drilled with an auger rig by Jim Cole of District 14. Upon notification that the hole was complete, Jack Bigham, Bill Schultz, and Lawrence Schultz, Horace Hoy, and I were lowered down through the 24-inch hole by a makeshift stirrup on the end of the kelly of the auger rig. Jack Bigham was the first to enter the cavern. When I was lowered into the cavern, I saw the drill pipe that Sylvan Turner had twisted off into the floor of the cavern. I recovered the drill pipe and bit and returned them to Sylvan to his surprise.

We explored the more accessible portions of the cavern and were surprised of its size and noticed that the air was stagnant because smoke from a match did not disperse readily and floated aimlessly in space. We had drilled into a cavern that had been undisturbed for some time and had only minimal openings to the outside.

District 14 personnel surveyed the cavern and mapped the major portion of it that was underneath the proposed overpass. I accompanied the survey crew. Some of the open core holes that were drilled into the original cavern room were utilized during our survey. We dropped light cords down the holes and illuminated the cavern during our survey. We spent several days in the cavern and found out early on that there was a shortage of oxygen in the cavern; therefore, we would only work short periods of time before returning to the surface.

During the following months numerous people entered the cavern for various reasons. Local members of the Texas Speleological Association mapped the cavern. Bill Russell and others mapped much more of the cavern than is presently open to the public. On several occasions I explored the cavern with spelunkers and paleontologists. Dr. Bob Slaughter of Southern Methodist University and Dr. Ernest Lundelius of the University of Texas visited the cavern.

One of my trips with some of the local spelunkers was on a particularly cold day in winter when the temperature outside was between 30 and 40 degrees Fahrenheit (F.). The spelunkers utilized a chain ladder to descend into the cavern through the vertical 24-inch entrance hole. We went into the cavern one Saturday morning and came out late that afternoon. Going down the chain ladder was not a problem for my boots were dry and I was fresh when I was descending into the warm cavern. Exploring the cavern we got sweaty due to its constant humid 72 degrees F. temperature and muddy from the very slick red mud that is common to Edwards formation caves. In the late afternoon when we decided to leave, I realized that I had a problem that no one else did in getting out of the cave. In order for me to climb from one chain ladder step to another (about 18 inches), I had to raise my leg to a horizontal position. To make a long story short, my 27-inch leg would not fit into a 24-inch-diameter hole; therefore, I had no choice but to chin myself up each step of the 33.5-foot hole so my muddy feet could slip into the next moving step of the chain ladder. With the cold air descending down the hole onto my sweaty body and the cheers from the spelunkers above, I somehow made it to the top. The experience was unforgettable.

The spelunkers were a big benefit to the THD by mapping the cavern for overpass design purposes. The engineers of the Bridge Division and District 14 felt that the 33.5 feet of competent limestone that occurs between the surface and the cavern was adequate to support the planned overpass. Also, the mapping that the spelunkers did was a helpful to Dr. William W. Laubach, the landowner, who later developed the cavern into what is now known as Inner Space Cavern.

Dr. Laubach asked and received permission from the THD to develop the cavern beneath Interstate 35. He accessed the cavern by excavating an artificial opening outside and adjacent to highway right-of-way. During construction of the cavern development, the original 24-inch core hole drilled by THD was used as an air vent. The construction of the overpass of Interstate Highway 35 covered the vent. The Inner Space Cavern opened officially in June 1966 and had its 25th anniversary in June 1991. It is reported to have had close to one million visitors during this time.

SOME GEOLOGICAL OBSERVATIONS ABOUT THE CAVERN

When I was lowered down the 24-inch drill hole to the cavern I observed that from the top of the ground to an unmeasured distance down the hole the limestone bedrock had the characteristics of the Georgetown formation. The remaining portion of the 33.5-foot hole and cavern area are within the Edwards formation. The upper section of the hole was a dry chalk-white nodular limestone of uniform lithology. Immediately below this, the lithology abruptly changed to a honeycombed, cherty, massive, dolomitic limestone with water flowing out of the honeycombed opening and down the wall of the core hole and dripping into the cavern below. Inside the cavern I observed numerous nodules and discontinuous beds of chert that are exposed. There are some places in the cavern where fossiliferous limestone beds resemble coquina. Much of the cavern is stained with various shades of red, iron oxide, and the floor is covered with red mud and in places with bat guano.

Paleontologists Drs. Bill Slaughter and Ernest Lundelius identified numerous extinct vertebrates. Some of those identified were peccary, mammoth, camel, dire wolf, horse, bat, rabbit, prairie dog, and saber-toothed tiger. There are several closed collapsed sinks identified by the spelunkers' mapping that were most likely natural openings at some time in the past for many of the bones were found in these areas.

Structurally the cavern is within the Balcones Fault Zone that has a general strike of North 15 to 25 degrees East in the area of the cavern. The cavern map reflects this primary strike as well as additional secondary cross faulting and jointing.

HYDROGEOLOGY AND KARST OF A NEW TOWN: CASE STUDY OF SUN CITY-GEORGETOWN, WILLIAMSON COUNTY, TEXAS

Michael R. Thornhill

INTRODUCTION

Development of land near and atop the Edwards Aquifer recharge zone raises many familiar concerns, and poses diverse challenges to property owners, developers, land planners, consultants and regulators alike. The satisfactory working out of the environmental, geologic, hydrologic, geotechnical, engineering, architectural, planning/design and political issues requires extensive and careful planning. It is well known in the Austin area that projects have been re-designed or even terminated because of these issues.

Recognizing the lure of the Central Texas Hill Country and the Austin area, the Del E. Webb Corporation (Del Webb) began plans to develop its newest Sun City community in the area. Of several considered sites, an approximately 5,300-acre tract about 5 miles west of the City of Georgetown in Williamson County was selected. Del Webb assembled a team of consultants to conduct due-diligence investigations to determine the feasibility of such a development. Once feasibility was determined, additional investigations were conducted to provide guidance in aquifer and habitat protection during and after development.

Dr. Charles Woodruff Jr., Mr. Mike Warton and R.W. Harden and Associates, Inc. (RWH&A) were engaged to evaluate the geologic and hydrologic conditions of the proposed site, particularly as related to recharge and the ground-water system of the Edwards Aquifer. Such investigations were used in submitting permit applications to the U.S. Fish and Wildlife Service (USFW) and to the Texas Natural Resources Conservation Commission (TNRCC). The primary emphasis of this work was locating and identifying caves (and related endangered species) and other potential recharge features (PRF's), and determining their potential importance. These and other tasks were conducted to develop a program of protecting important features during construction, evaluating additional features discovered or uncovered during construction, and in planning final development layouts to provide appropriate buffers around important features.

GROUND-WATER CONDITIONS

RWH&A conducted a preliminary study of the geologic and hydrologic conditions in the vicinity of the Sun City-Georgetown development. This investigation included a review of past applicable RWH&A work, readily-available geologic and ground-water reports, selected maps, aerial photographs, ground-water data, well records, and drillers' logs. Also, site investigations included a well and spring inventory in which water levels were measured where possible, and limited water quality sampling was conducted.

Regional Setting

The Sun City-Georgetown property overlies a small part of the Northern Segment of the Edwards Aquifer. As in other portions of the Balcones Fault Zone, the Edwards is characterized by bedded carbonate units exhibiting karst characteristics and features.

However, faulting in the Northern Segment is less pronounced, and thus affects groundwater flow less than in other segments. This is evidenced by a less drastic change in the artesian portion of the aquifer from generally good quality water to more highly mineralized water (i.e., the "bad water line").

Generally, recharge occurs to the Edwards Aquifer via direct infiltration from precipitation and by seepage from streams on the outcrop of the Edwards. In contrast to the San Antonio and Barton Springs Segments of the aquifer, where most recharge occurs along stream reaches crossing the Edwards outcrop, the Northern Segment receives a lower proportion of its recharge from streamflow losses (R.W. Harden & Associates, 1994). The Sun City-Georgetown property represents about 2 percent of the total recharge area of the Northern Segment.

After water is recharged to the aquifer within the Northern Segment, it moves generally eastward in the recharge zone toward the downdip or artesian portions of the aquifer. However, regional studies indicate that significant flow is northward, approximately along and parallel to the recharge-artesian zone boundary, partly coincident with larger north-south trending faults. Prior to the aquifer being tapped by wells, most of the discharge from the Edwards occurred through springs, with a small amount occurring via leakage to overlying formations in the downdip artesian area. Notable springs include San Gabriel Springs and Berry Springs near Georgetown, and Salado Springs at Salado. Pumpage, primarily for municipal and industrial supplies in and near the Cities of Pflugerville, Round Rock, and Georgetown, has caused springflows to decrease such that San Gabriel and Berry Springs go dry during periods of low rainfall.

Site Conditions

The Edwards Limestone underlies the entire Sun City-Georgetown property, and appears at the surface over most of the property, resulting in gently rolling topography with some steep drainages incised into the more resistant beds. Based on drillers' logs, the Edwards probably ranges up to 130 feet thick. Some minor thicknesses of overlying Georgetown Limestone may be present on parts of the property, and minor thicknesses of alluvial and terrace deposits are present at some locations, primarily along larger streambeds.

Based on descriptions in drillers' logs that indicate larger openings, and based on extensive experience in the area, "lost returns" zones, caves, or cavernous conditions are encountered in up to about 10 to 20 percent of holes drilled. Also, these zones or zones where the drill bit actually drops (indicating a void) typically are less than 1 to 3 feet in thickness. The frequency and occurrence of such zones tend to be higher in and near the outcrop.

Common karst features, such as fractures, caves, sinks, vuggy limestone, and solution cavities transmit water to the aquifer. Such recharge is dependent upon openings, soil character, vegetative conditions, antecedent rainfall, and associated drainage area. Many identified karst features are relict karst features within topographically high upland areas. Generally, only a few features exhibited significant catchment areas so as to be considered important recharge features.

A few small perennial springs, and one larger spring were located during field work. Cowan Spring was observed to flow between about 30 to 150 gallons per minute (gpm) during dry and wet cycles respectively, and was the largest perennial spring located. Cowan Spring provides much of the flow for Cowan Creek on the property. One ephemeral spring was reported, and later observed to flow from an excavated solution-enlarged fracture. This spring, named Resurgence (Emergent) Spring, is located in a draw along Berry Creek; it flowed up to about 2,000 gpm during higher stages of the aquifer. During dryer periods, the water level falls to several feet below ground level. Other small ephemeral springs and seep areas were also located during later site investigations.

Water levels were measured in accessible wells in the vicinity of the site. Depths to water ranged up to about 120 feet below ground level at topographically higher areas. Water-level elevations indicate that ground water flows generally from west to east and toward the major drainages, Berry and Cowan Creeks. Cowan Creek is a gaining stream until near its confluence with Berry Creek. Historical data indicate that water levels fluctuate several feet due to recharge-discharge fluctuations.

Based on geologic settings and streamflow studies (Harden, 1994), Salado, Dry Berry, and Brushy Creeks provide most of the streamflow losses to the Northern Segment (Figure 1, Major Drainage Basins - Edwards Aquifer Northern Segment). Sun City-Georgetown lies within the Berry Creek drainage basin, and Berry Creek flows across the property. While likely at least half of the recharge to the entire Northern Segment is from direct infiltration on the outcrop, recharge estimates indicate that Berry Creek streamflow losses provide over half of the recharge on the Sun City-Georgetown property. Cowan Creek discharge (mostly derived from Cowan Spring) is lost to seepage into Berry Creek. The amount of recharge from Berry Creek seepage varies with the stage of the aquifer and flow conditions within the creek.

Ground water that moves past discharge areas (i.e., springs, seeps, wells) on the Sun City-Georgetown property, moves downdip to other springs and wells and to artesian portions of the aquifer. Some water moves toward the City of Georgetown; most probably moves northward toward Bell County.

Edwards water beneath the property is generally of good quality. The water is hard, containing calcium and magnesium, with relatively low total dissolved solids (i.e., 300-400 mg/l).

POTENTIAL RECHARGE FEATURES

Initial mapping of potential recharge features included locating surface expressions of possible caves, cavernous features and other significant karst features. Woodruff utilized aerial photography and field investigations, and Warton traversed the property to locate such features. Geophysical techniques were utilized by Gasch and Associates of Sacramento, California, to attempt to find subsurface karst openings with no surface expressions. These investigations were primarily directed at locating habitat caves, but were also utilized in aquifer protection. Of over 300 initial potential karst sites, 87 caves were identified. Caves were entered and mapped by Warton (Figure 2, Cave Dimension Diagram - Reach Around Cave, Prepared by Mike Warton). Most caves (82 percent) located are shallow (less than 10 feet), bedding plain caverns with thin openings (1 to 2 feet) and limited aerial extent. Endangered species were identified in 26 caves, and

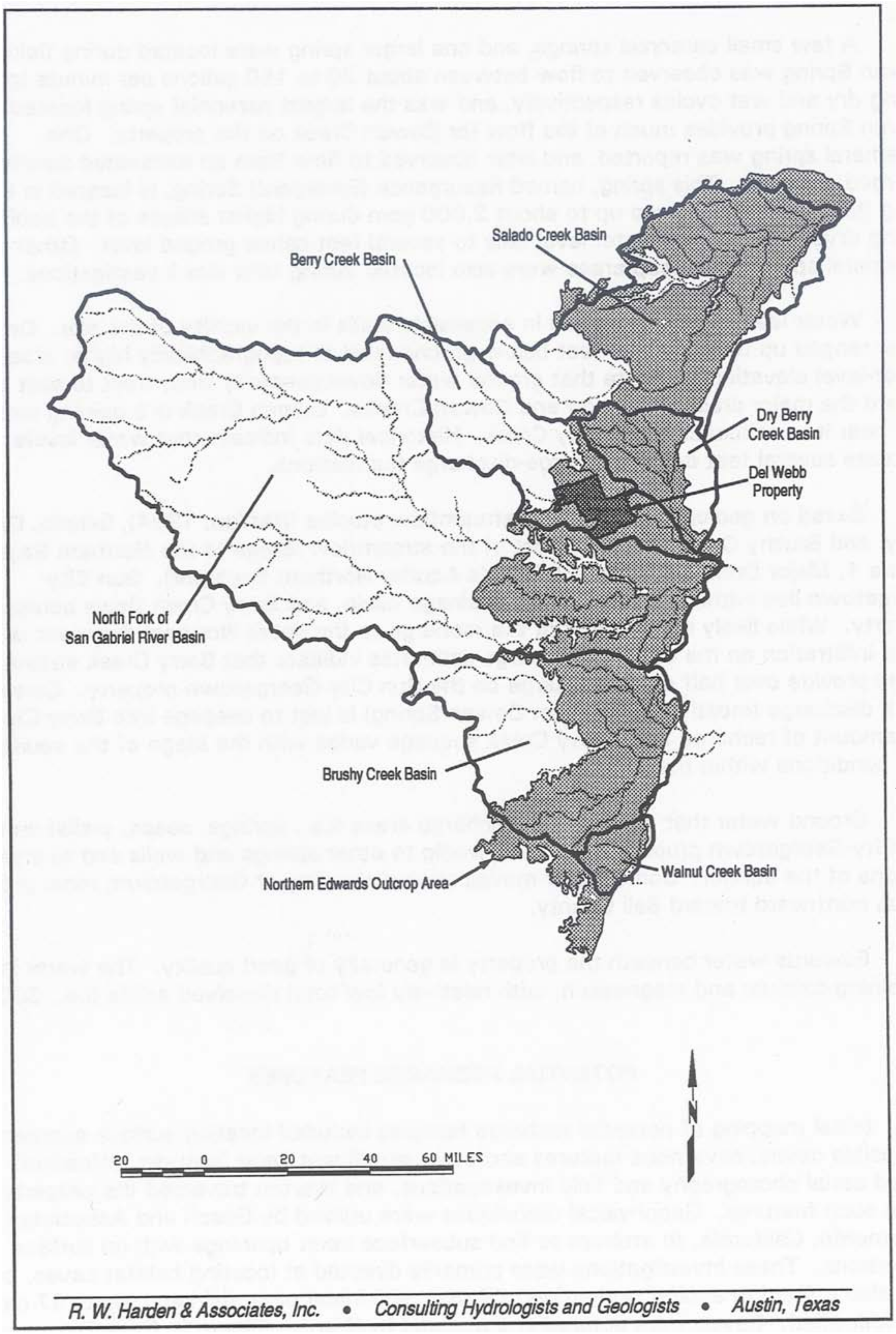


Figure 1. Major Drainage Basins - Edwards Aquifer Northern Segment.

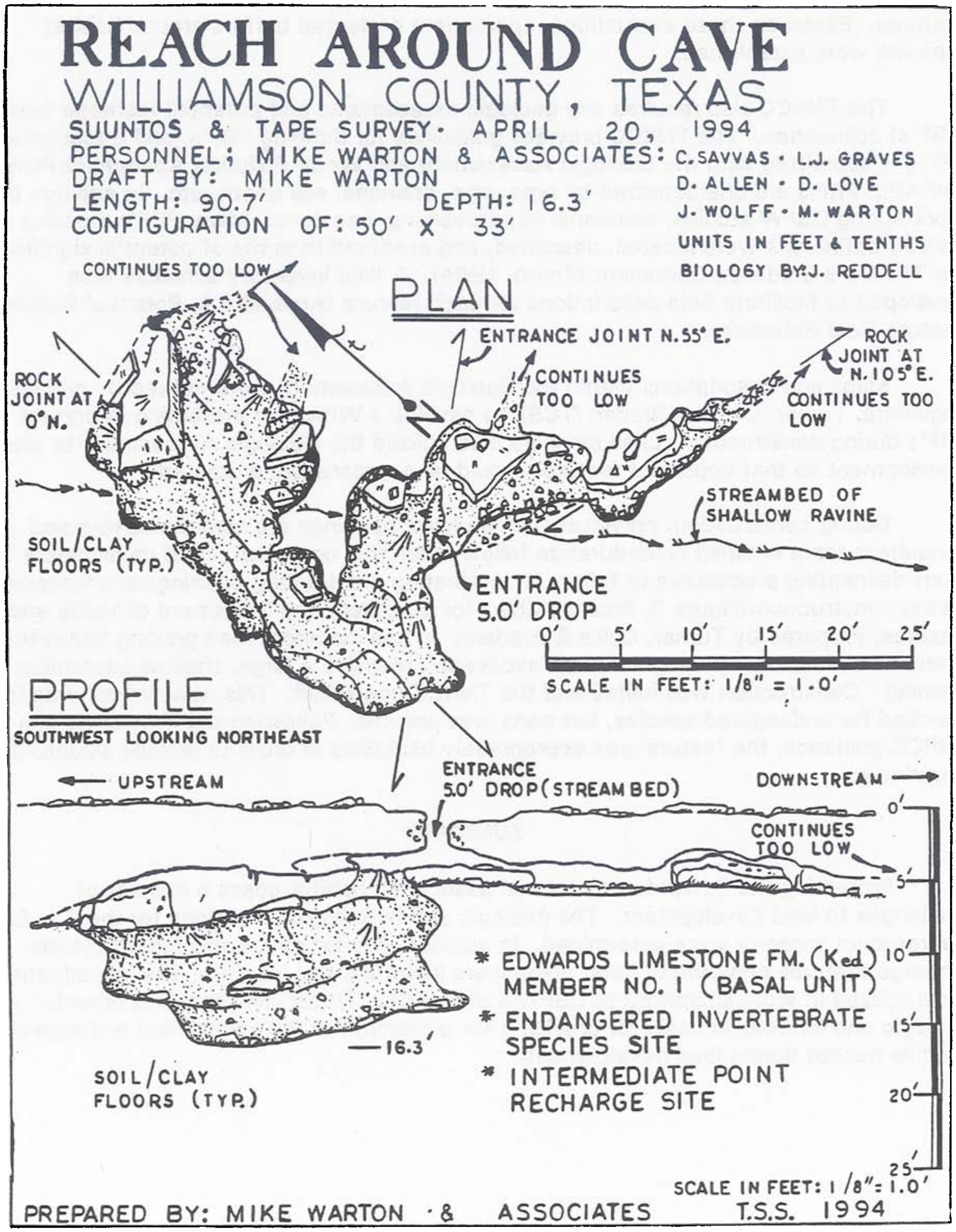


Figure 2. Cave Dimension Diagram - Reach Around Cave, Prepared by Mike Warton.

detailed site recharge features evaluations were conducted within 300 feet of habitat features. Based on these evaluations, appropriate protected buffers around habitat features were established.

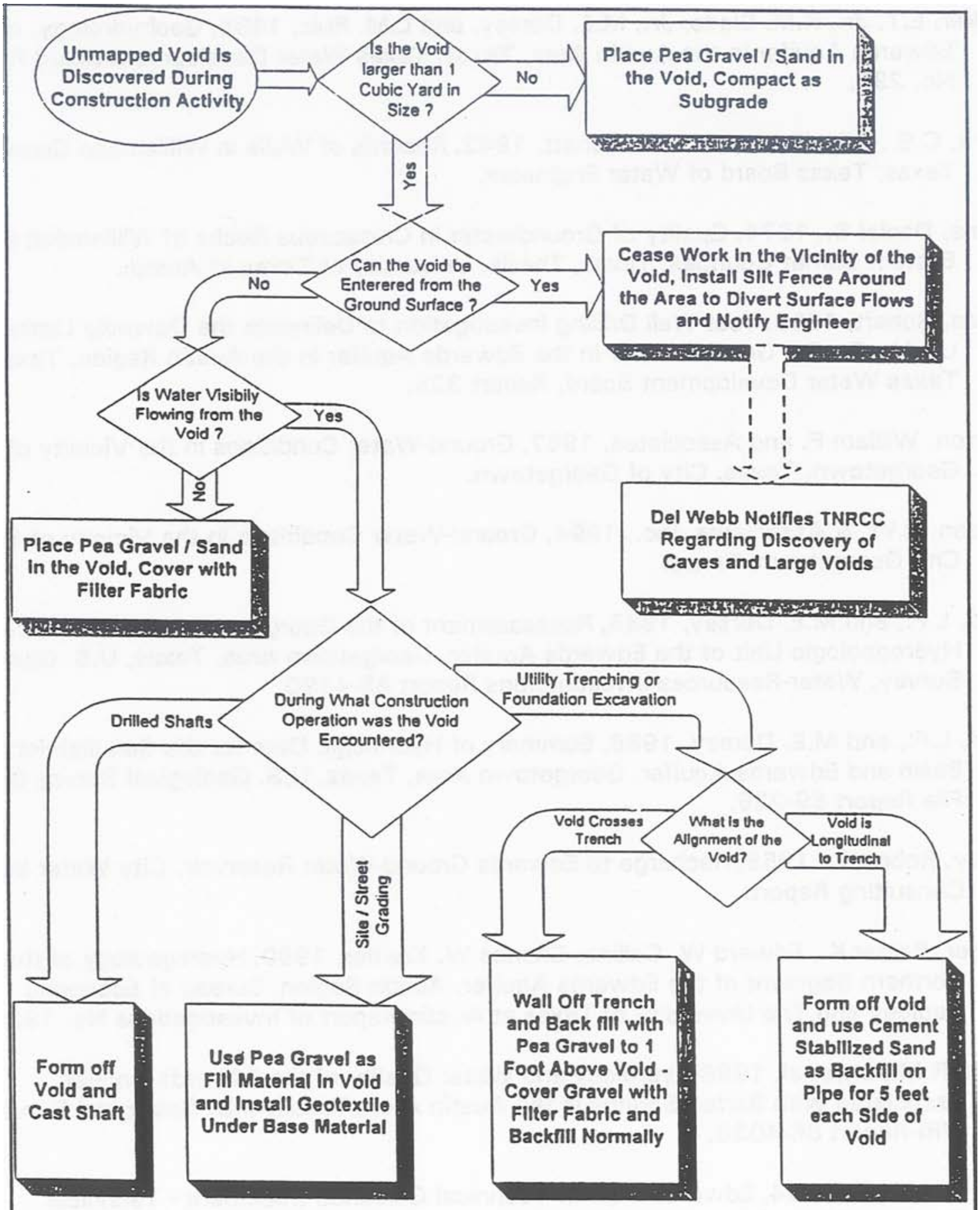
The TNRCC also requires site geologic assessments and potential recharge feature (PRF's) delineation. The TNRCC provides guidelines for defining PRF's, and a tabulation of PRF's is submitted with the Geologic Assessment and Water Pollution Abatement Plan (WPAP). PRF's are characterized by type, size, drainage, soil depth, etc. In addition to work during USFW studies, additional site traversing was done. Many PRF's meeting TNRCC definitions were located, described, and assessed in terms of potential significance, per TNRCC's Guidance Document (Smith, 1994). A field inventory schedule was developed to facilitate field descriptions for each feature (Appendix A, Potential Recharge Feature Field Schedule).

Maps and descriptions within the Geologic Assessment were utilized by project engineers, Turner, Collie & Braden (TCB), to develop a WPAP for protecting important PRF's during construction. Land planners also utilized the Geologic Assessment to plan development so that important features would be appropriately protected.

During construction, previously hidden karst openings are sometimes revealed. The consultant team outlined procedures to follow when this occurred. TCB developed a flow chart delineating procedures to follow for evaluating and treating openings encountered during construction (Figure 3, Process Chart for Discovery and Treatment of Voids and Fissures, Prepared by Turner, Collie & Braden). In one instance, road grading uncovered a small, karst fracture opening. A small excavation revealed a large, shallow cavernous opening. Construction was halted and the TNRCC contacted. This new "cave" was then checked for endangered species, but none was present. Following the flow chart and TNRCC guidance, the feature was appropriately backfilled in order to provide structural soundness.

SUMMARY

Protecting the Edwards Aquifer and associated habitat poses a number of challenges to land development. The geologic and hydrologic conditions for the Sun City-Georgetown property were determined. In addition, habitat caves and other potential recharge features common to karst areas were identified and located. The investigations were utilized in work submitted to USFW and TNRCC. These investigations provided a geologic and hydrologic basis for providing for protection of the aquifer and endangered species habitat during land development.



PROCESS CHART FOR DISCOVERY AND TREATMENT OF VOIDS AND FISSURES

Figure 3. Process Chart for Discovery and Treatment of Voids and Fissures, Prepared by Turner, Collie & Braden.

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R. W. Harden & Associates, Inc.
Potential Recharge Feature (PRF)
Field Evaluation Form

Project:____________________ **County:**______________________________
Aquifer:____________________ **Topographic Quadrangle:**____________(name)
____________(state no.)

Land Owner: (Name) ______________________________
(Address) ______________________________
(Phone) ______________________________

Feature Identification and Location

Number:________________

Coordinates: (x)________(y)________ Source: GPS, Survey, Estimate (circle one)

Land Surface Elevation________(ft. AMSL) Source: GPS, Survey, Estimate (circle one) Topo (Scale _____ C.I. _____ ft.)

Is feature on project site or downgradient? ______________________

Location Description: ______________________________

Feature Type (circle one)

Cave	Man Made
Closed Depression	Rapid Infiltration
Fault Zone	Solution Cavities
Fractured Rock Outcrop	Sinkhole
Vuggy Rock Outcrop Zone	Other ______________

Describe: ______________________________

Physical Setting

Condition of Feature Upon Inspection: (excavated, natural, etc.) ____________

Geologic Formation: ______________________________

Drainage Area in Acres (circle one)

<1 1 - 9 10 - 50 >50

How determined and describe: ______________________________

Topography (circle one)

Top of Hill Hillside Vertical/Near-Vertical Wall Valley Floor

Stream Bed In 100-year flood plain (source________________)

Soil Cover (Type, thickness, etc.)______________________________

Vegetative Cover (Type, density, etc.)______________________________

Comments: ______________________________

R. W. Harden Associates, Inc., Consulting Geologists and Hydrologists

Appendix A. Potential Recharge Feature Field Schedule.

Feature Characteristics

Dimensions: Depth ________ (ft.)   Diameter ________ (ft.)
Length ________ (ft.)   Width ________ (ft.)

Describe: ____

____

Density of Rock Openings (circle one)   Low   Moderate   High

Describe: ____

____

Infilling (Type, thickness, etc.) ____

____

Trend (Azimuth): Primary ____________ ° Secondary ____________ °

Pattern (linear, parallel, circular, radial, etc.) ____________________

Assessment

Connection to Aquifer (circle one)   None Apparent   Possible   Probable

Explain: ____

____

____

TNRCC Significance (circle one)   None   Low   Moderate   High

Explain: ____

____

____

Additional Comments, Drawings, Etc.

Recorded by: ____

Source: ____

Date: ____

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R. W. Harden Associates, Inc., Consulting Geologists and Hydrologists

Appendix A. Potential Recharge Feature Field Schedule - Continued.

THE LAKELINE TRILOGY: A STORY OF A SHOPPING MALL AND TWO CAVE BUGS

C. Lee Sherrod

In 1986, national mall developer Melvin Simon & Associates, Inc. purchased a 116-acre site near the intersection of US 183 and FM 620 on the northwest side of Austin, in Williamson County, Texas (Figure 1), with the intent of developing one of the largest retail shopping malls in the southwestern U.S., to be named Lakeline Mall. The Austin area was then at the apex of a growth boom and the vicinity of the mall site was rapidly urbanizing, in effect blending the City of Austin with the cities of Cedar Park and Round Rock to the north.

Melvin Simon proceeded forward with site design and local development approvals through the City of Austin which was an arduous and lengthy process requiring several years for a major project such as the mall. The site was located within the Edwards geologic formation, a formation typically associated with geohydrologic recharge of the environmentally sensitive Edwards Aquifer. For developments located within this geologic formation, local development codes required detailed geologic assessment to determine the presence of significant aquifer recharge features (caves, sinks, fissures, etc.) and appropriate protective measures. Charles Woodruff, consulting geologist, conducted detailed geologic studies of the site including corings to determine subsurface characteristics. Numerous karst features (voids) were documented on the site including several caves and large sinks; however, Woodruff concluded the site was part of an isolated remnant of the Edwards formation that no longer connected hydrologically with the Edwards aquifer and that the on-site karst features were not significant from an aquifer recharge standpoint. This assessment in part cleared the way for local development approvals over the next several years. By late 1989, site design was complete and local approvals were imminent. Construction of the mall was anticipated to begin in early 1990.

Meanwhile, a few miles to the south in another portion of the Edwards formation, development/antidevelopment battles were raging over exploding growth in the western part of Travis County. In the fracas, two species of birds and five species of cave-adapted (troglobitic) invertebrates were listed by the U.S. Fish and Wildlife Service as endangered species. When listed in 1988, the cave invertebrates were thought to be restricted to just a few caves located in a relatively small geographic area of western Travis County and a few isolated outliers in Williamson County to the north. These species were not then known to occur in the immediate vicinity of the mall site.

In late 1989, spelunkers were exploring caves in the vicinity of the mall site, and in one cave, to be named Lakeline Cave due to its location on the edge of the proposed mall site, found what they believed to be one of the listed cave invertebrates, the Tooth Cave ground beetle (*Rhadine persephone*). In January 1990, James Reddell of the Texas Memorial Museum conducted a biological survey of the cave at the behest of the U.S. Fish and Wildlife Service and confirmed the presence of the Tooth Cave ground beetle as well as another listed invertebrate, the Bone Cave harvestman (*Texella reyesi*) (Figure 2). The U.S. Fish and Wildlife Service notified Melvin Simon of the presence of the listed species and that a prohibited taking of those species in Lakeline Cave and possibly other caves on the mall site might result from the proposed mall development activities. The possible presence of the listed species in any of the other caves or karst features on the site was

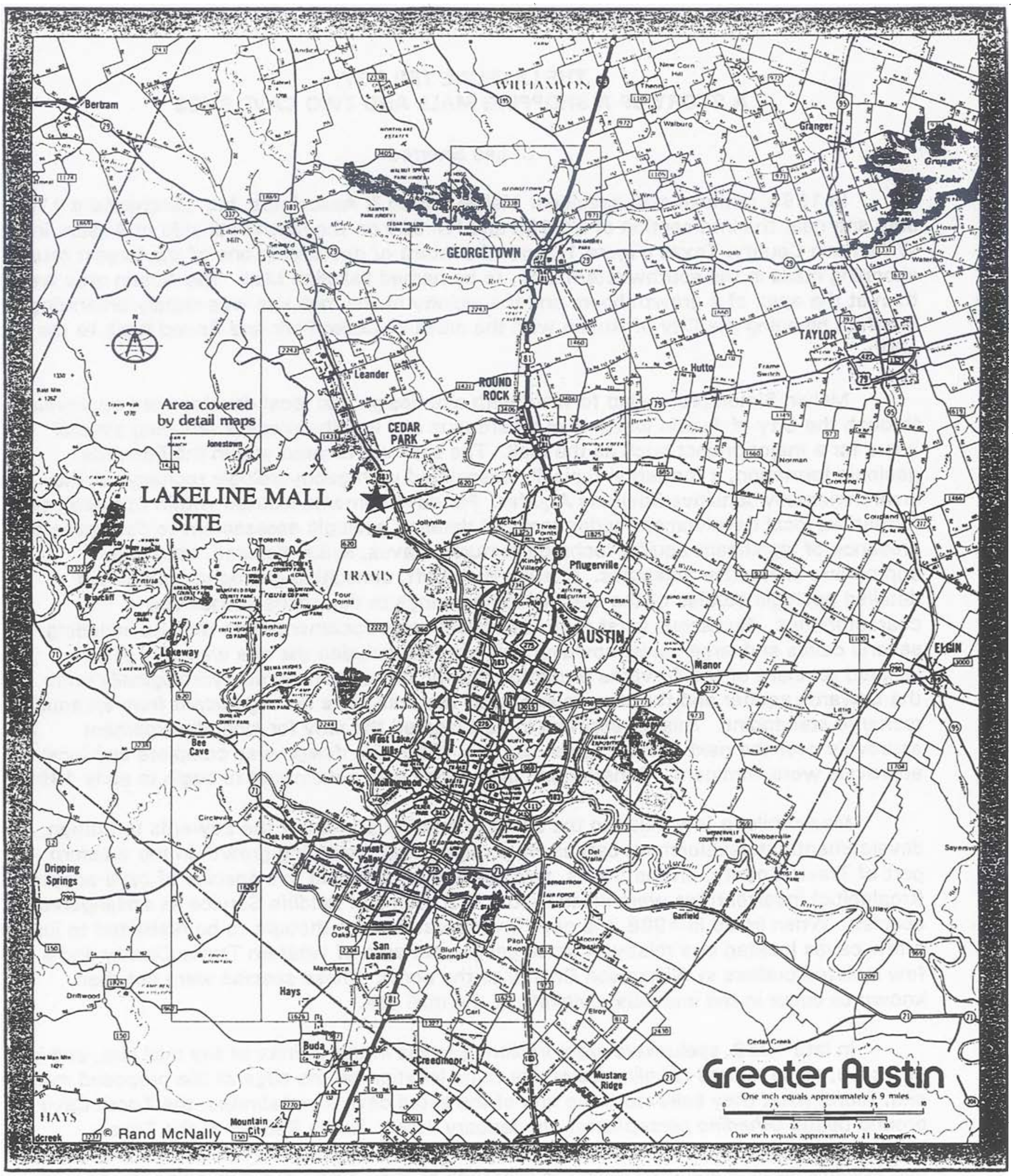
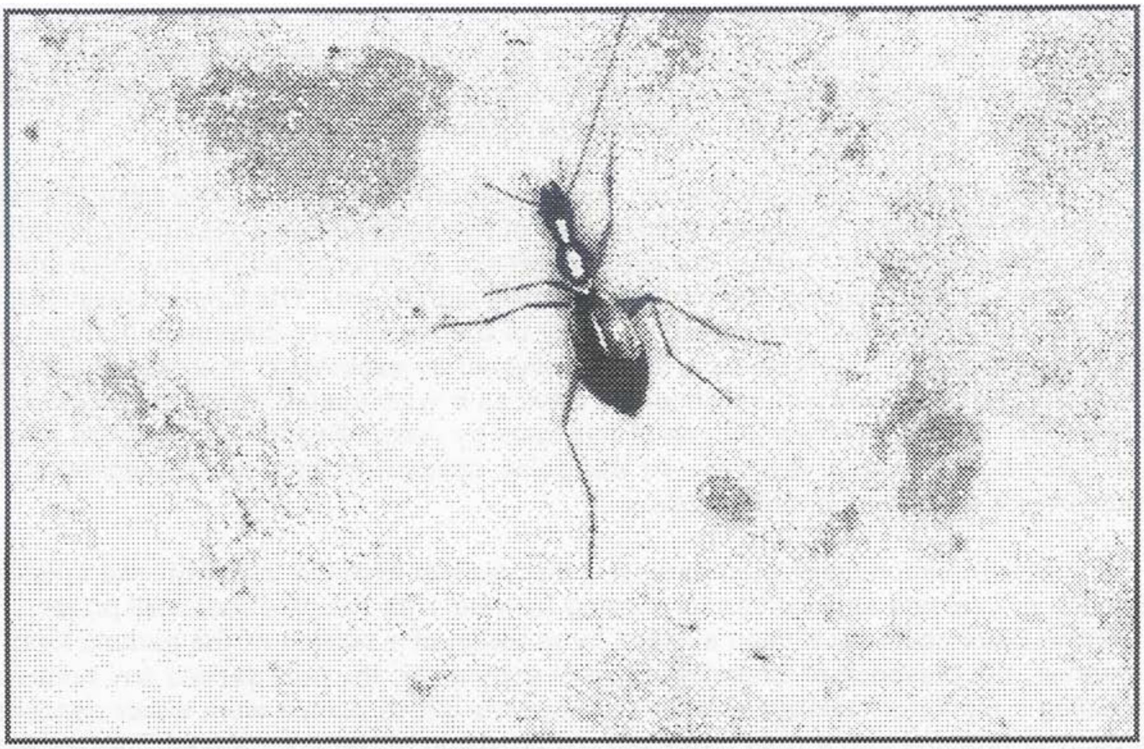
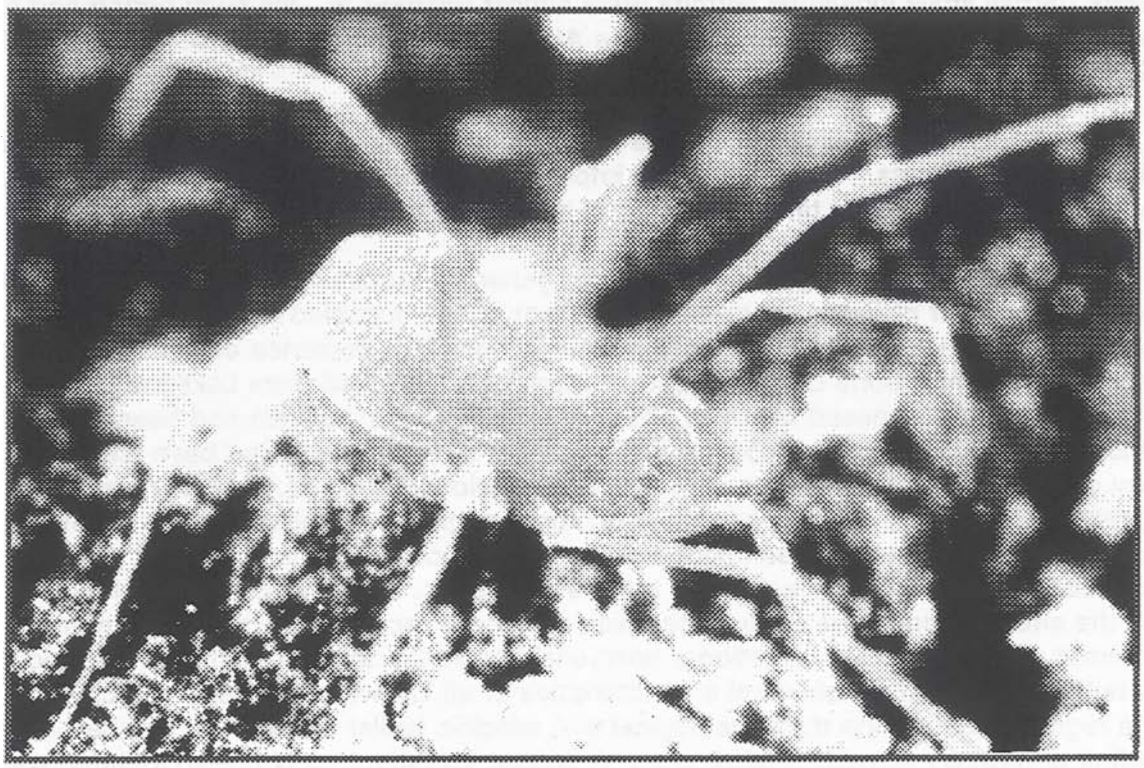


FIGURE 1
LOCATION MAP



Tooth Cave Ground Beetle

Photograph by: Wyman Meinzer, for U.S. Fish and Wildlife Service.



Bone Cave Harvestman

Photograph by: Robert W. Mitchell.

FIGURE 2

CAVE INVERTEBRATES

unknown at that time. Melvin Simon, still in anticipation of starting construction soon, immediately commissioned detailed karst investigations on the site to attempt to determine the presence or absence of the invertebrates elsewhere on the site.

These initial studies by Horizon Environmental Services, Inc. and Mike Warton & Associates included a comprehensive review of the karst features previously identified by Woodruff in addition to further site reconnaissance efforts to identify any other potential karst features that might prove to be biologically significant. The karst assessment included excavation and exploration of many of the features to determine if enterable caves were present. One enterable cave was discovered by excavation of a mostly filled sink feature. The cave was named Underline Cave as it was located under the proposed mall (Figure 3). Biological investigations of this cave by James Reddell revealed the presence of the listed Bone Cave harvestman. At this point, nearly 6 months had transpired and the mall project as now in indefinite delay.

Melvin Simon conducted extensive discussions with the U.S. Fish and Wildlife Service to evaluate alternatives for moving forward with the proposed mall project. Lakeline Cave could have been avoided by redesign of a portion of the parking lots; however, the presence of Underline Cave directly under the mall dashed any hopes of avoiding a regulatory takings and the only options left to pursue were either cancel the mall project or proceed into a then rarely utilized provision of the Endangered Species Act, a 10(a) permit for incidental taking of endangered species. The 10(a) permit process (referenced in Section 10 (a)(1)(B) of the Act) was instituted by Congress in 1984, but by 1990, only a small handful of such permits had been issued nationwide and most of those had been issued in California, Oregon and Florida on a large-scale regional and institutional basis. Small scale individual permits were almost unheard of. No such permit had ever been processed or even applied for in the Albuquerque Region of the U.S. Fish and Wildlife Service (covering the subject area).

Melvin Simon elected to pursue the permit option despite great uncertainties as to time frames or costs. When Congress implemented 10(a) permit provisions in 1984, no processing guidelines or time frames were included.

The 10(a) permit application process generally requires the determination of the type and number of listed species or the extent of the occupied habitat to be taken. In the early stages of Lakeline's permit application process, the presence of the Tooth cave ground beetle and Bone Cave harvestman had been identified from Lakeline Cave on the periphery of the proposed mall site and the Bone Cave harvestman had been identified from Underline Cave under the proposed mall. Neither of the species had been identified from any of the other karst features on the site. Questions remained, however, as to the total extent of potentially suitable karst habitat for occupation by these species on the site and whether or not these species might exist in subsurface voids that were not directly associated with major surface karst features or caves. The previous geotechnical corings on the site had identified subsurface voids at various locations on the site. In order to attempt to answer these questions, additional investigations were initiated that included a detailed analysis of geophysical characteristics of all known endangered species caves in the region to determine those geological and edaphic (soils) characteristics that would best define potentially suitable habitat area. A unique investigation was also initiated that was aimed at trying to sample the invertebrate fauna of inaccessible subsurface voids.

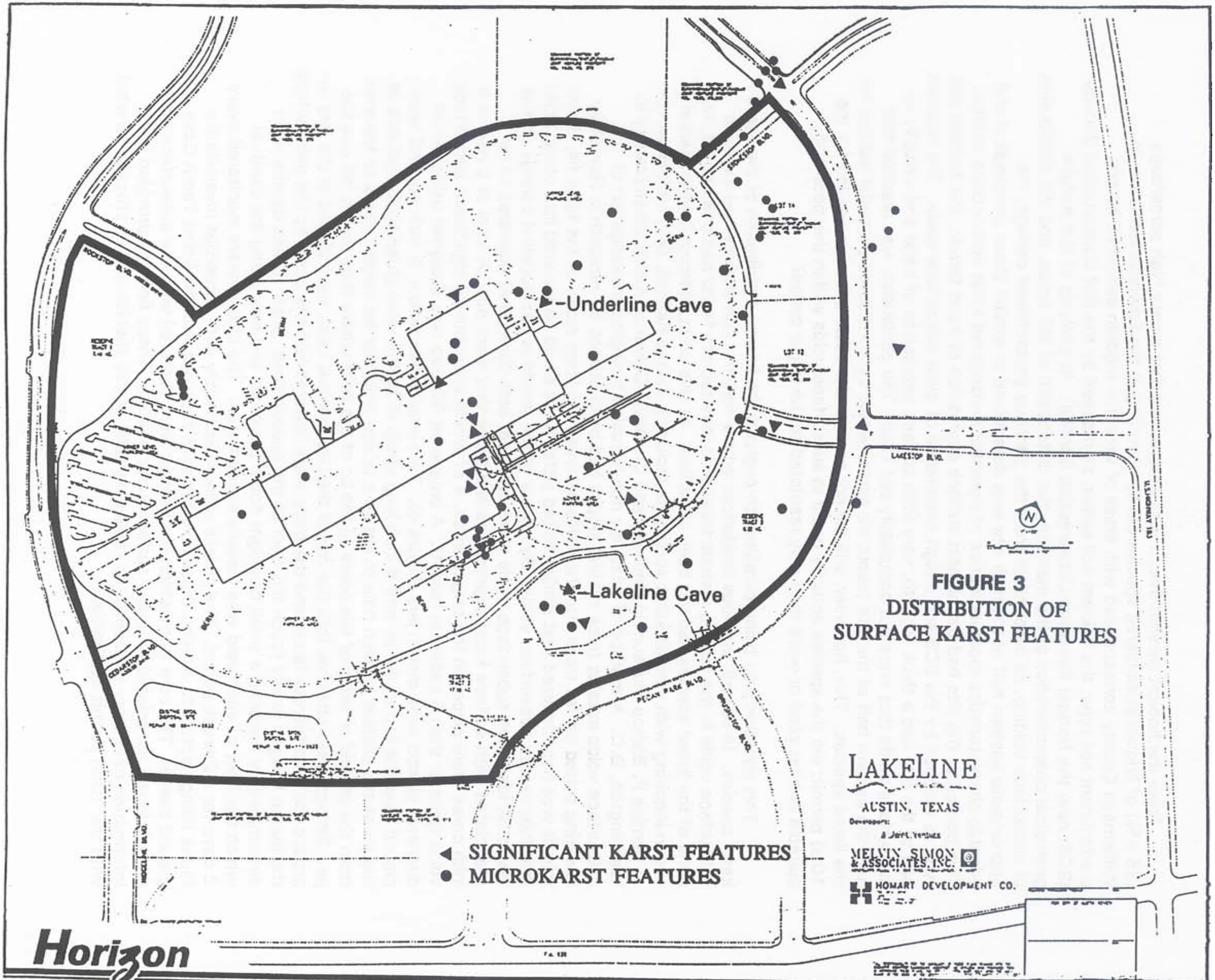


FIGURE 3
DISTRIBUTION OF SURFACE KARST FEATURES

Horizon
ENVIRONMENTAL SERVICES, INC.

From the habitat perspective, it was determined that a very high percentage (95+%) of known endangered species caves occurring in the Edwards formation in Williamson County corresponded with areas of very thin regolith described by one predominant soil type, the Eckrant soil series, as mapped by the Soil Conservation Service (SCS, now the Natural Resource Conservation Service). In analysis of the surface geological characteristics of the mall site, the distribution of soil types, and the distribution of subsurface voiding, as determined from the previous geotechnical corings, the approximate eastern half of the mall site was determined to exhibit those geophysical and edaphic characteristics most indicative of potential endangered karst invertebrate habitat. This portion of the site had the highest surface expression of karst terrain, the Eckrant soil type as mapped by the SCS and a high occurrence of open subsurface voids. The western half of the site had a thick regolith, very little surface expression of karst and virtually no subsurface voids that were not completely soil filled. The conclusion was reached that only the eastern half of the site (about 62 acres) would be considered potential habitat for the listed species. This, however, still did not answer the basic question needed for the 10(a) permit; did the species actually occur in subsurface voids within this potentially suitable habitat zone or were they only restricted to the larger caves?

This question was being pondered throughout the known distribution of the listed karst species. In several previous incidences where construction activity had exposed subsurface voids in the region, various troglobitic invertebrate fauna had been noted, but none of the listed species had yet been identified. At this point, Horizon Environmental began inquiring with various karst ecologists including James Reddell, Dr. Frank Howarth of Bernice P. Bishop Museum in Honolulu and Dr. David Culver of American University in Washington, D.C. A method of relatively non-intrusive biological investigation of subsurface voids in talus (rock rubble) slopes had been utilized by Howarth in Hawaii by lowering baited pit fall traps into the voids between the large rocks of the talus fill. From this, it was hypothesized that similar baited pitfall traps could be lowered into cored holes that intercepted subsurface voids. By review of the previous geotechnical corings on the mall site, identified subsurface voids were targeted, both those that appeared to be associated with surface karst expressions and those that were not. A total of 6 new 4.5-inch cores were placed in the target areas, 4 of which encountered significant subsurface voids (greater than 6 inches in height). A unique pit fall trap was designed using 4-inch diameter plastic wide mouth jars (Figure 4). Two small holes (about ½ inch square) were placed near the top of the jar and 6-inch long strips of burlap were glued to the outside of the jar at the bottom of each hole to act as a bridge or ladder for invertebrates to traverse from the ground or sides of the cores to the lip of the hole where they would fall into the jar. Strings were attached into the lids of the jars, various baits were placed in the jars to attract the invertebrate fauna and the traps were lowered into the cores to the point where the burlap bridges would touch the floor of the encountered voids. These depths were determined by lowering a small flashlight down the cores and measuring the depth at which the floor of each void was visually encountered. The pitfalls were monitored every 2 days for a 2-week period. The pitfalls worked admirably with numerous invertebrate fauna being captured. Among those invertebrates captured was the listed Tooth Cave ground beetle. The core from which the beetles were captured was in a subsurface void not obviously associated with any surface karst feature. These findings provided the information necessary to assess the regulatory take of the species and to proceed forward with the 10(a) permit application.

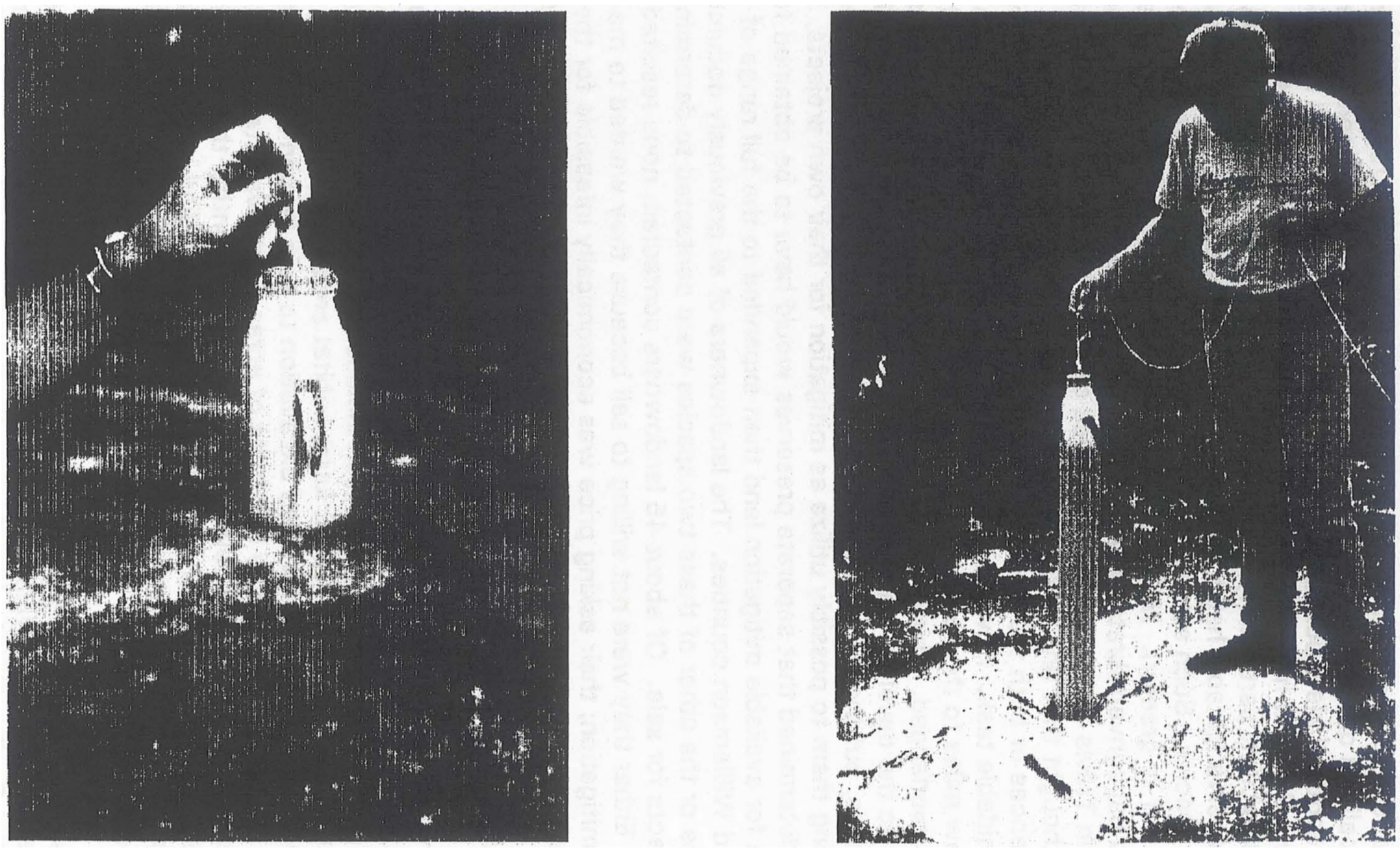


FIGURE 4
CORE TRAPS

A year had now expired since the first finding of endangered species in Lakeline Cave. However, the saga was far from conclusion. Because the Austin area was in the throws of attempting to develop a regional 10(a) permit to address broader endangered species issues throughout western Travis and Williamson Counties, the Lakeline permit effort required considerable coordination and informal approval by the regional permit sponsors (a large coalition of local governmental, development and environmental interests with a very wide breadth of view points). Determining and gaining approval of mitigation requirements became the next major hurdle. The typical mitigation scenario for endangered species habitat, particularly with karst habitat that cannot be readily recreated, is to acquire and preserve suitable habitat for the affected species that is documented to be occupied by the species. Such set aside is usually at some multiplied ratio to the area impacted (i.e., 2:1, 3:1 or greater). Melvin Simon engaged its consultants to locate suitable endangered cave invertebrate habitat that could be purchased for preserves. The Edwards formation in Travis and Williamson counties covered many thousands of acres and it was initially thought that finding the required amount of acreage (234 acres) with documented occurrences of both the Tooth Cave ground beetle and Bone Cave harvestman would not be a formidable task. However, as it turned out, the Lakeline area and a narrow zone stretching a few miles to the south along Hwy 620 was the only area in which the two species ranges overlapped. This area was some of the most expensive real estate in the Austin area due to the development potential. Several caves in this area were known to contain both species, but these caves were either already dedicated for preserves or the owners were retaining them to possibly utilize as mitigation for their own projects, if necessary. It was determined that separate preserves would have to be obtained for each species. The search for available mitigation land then expanded to the full range of both species in Travis and Williamson counties. The landowners of all previously documented caves containing one or the other of these two species were contacted to determine availability of the tracts for sale. Of about 45 landowners contacted, none resulted in a potential purchase. Either they were not willing to sell because they wanted to maintain their own potential mitigation; their asking price was economically infeasible for the Lakeline project; the parcels were too big and the owner would not subdivide; or the parcel was too small to be considered a viable cave preserve tract. The months were still passing and as yet resolution to the permit was not in sight.

Melvin Simon's consultants began reviewing parcels of land that were located in the Edwards formation but had not previously been investigated for karst habitat or the listed species. Several large parcels were studied which included surface karst reconnaissance efforts to locate potential caves or significant karst habitat areas and detailed investigations of many features which involved excavation to gain human access and then biological sampling. In this process, many hundreds of acres were evaluated and at least 8 new endangered species caves were discovered. After several months, the mitigation acreage containing several caves for both species was finally identified in three separate parcels within Williamson and Travis counties (Figure 5). Options were taken on the properties and the permit process took another step forward.

In the meanwhile, extensive negotiations had continued with the regional 10(a) permit group and the U.S. Fish and Wildlife Service over other terms of mitigation and permit conditions. The finally agreed mitigation plan included the 234 acres of karst preserves, provision of funding for management of these preserves, cash contributions to the regional 10(a) permitting effort, and funding for a 10-year cave research program. All to compensate for an estimated take of about 62 acres of suitable karst habitat and three

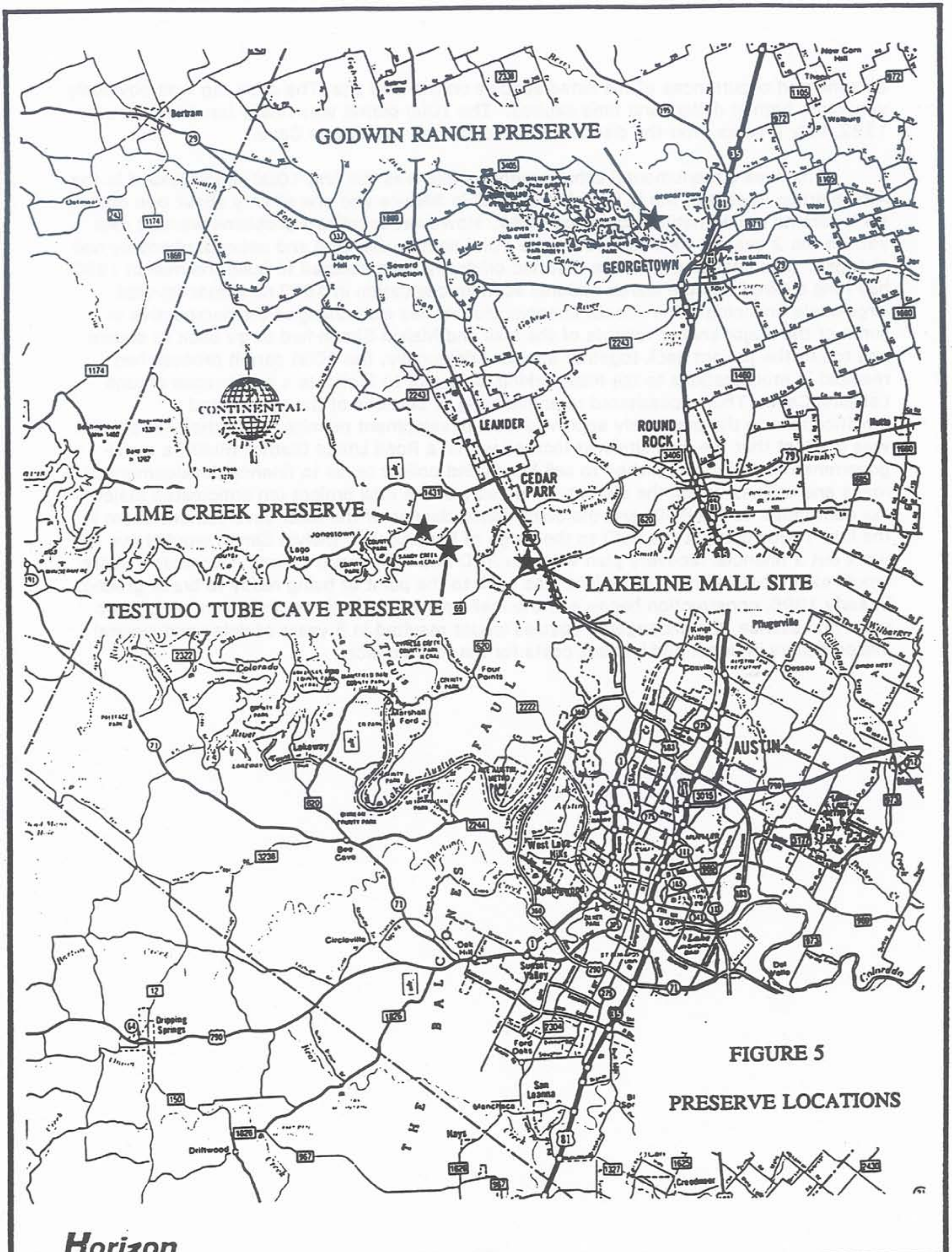


FIGURE 5

PRESERVE LOCATIONS

documented occurrences of the listed species on the mall site. The price tag was obviously very high, both in dollars and time expired. The 10(a) permit was finally issued in January 1992, fully 2 years after the discovery of the species in Lakeline Cave.

This was a monumental achievement as this was the first 10(a) permit issued in the Albuquerque Region of the U.S. Fish and Wildlife Service and one of only about two dozen such permits issued nationwide since 1984. However, Lakeline's problems weren't over yet. In the 2 years it took to achieve the 10(a) permit, the local and national economy had changed. The financing package that had originally been secured to build the mall in 1990 had long expired and the leaner national economic situation in 1992 no longer favored large-scale financing. The leaner financial picture had also changed the perspective of some of the major anchor tenants of the mall and Melvin Simon had to go back to square one to put the project back together again. Additionally, the 10(a) permit process had resulted in modifications to the mall parking lot layout to facilitate a buffer zone around Lakeline Cave. This necessitated re-engineering of portions of the project and modifications to the previously approved local development permits. A further compilation was the fact that the mall site was located within a Road Utility District (RUD), a quasi-governmental entity established to sell bonds and collect taxes to finance development of roads and utilities within the district. The delay of the mall project (an anticipated major tax contributor to the RUD) and the coincidental decline of the local development boom in the late 1980s brought the RUD to the verge of bankruptcy. Melvin Simon would have to work out a financial recovery plan with the RUD and Williamson County. Another 3 years would expire before the mall project was back to the point of being ready to break ground. In early 1995, construction began and the mall opened for business in November of that year. In essence, the endangered species issues resulted in 5 years of delay and several million dollars in direct and indirect costs for the mall project.

URBAN KARST ROAD LOG

C.M. Woodruff, Jr., and David R. Wuerch

Mileage

0.0 Depart Sid Richardson Hall parking lot, Manor at Red River; proceed south on Red River.

0.7 Turn right on 15th Street; proceed west.

1.0 Cross North Congress Avenue; continue west.

1.5 Cross West Avenue; descend into valley of Shoal Creek.

1.6 After crossing the viaduct over Lamar Boulevard, note "washboard road" typical of roads placed on Del Rio Clay; proceed west on Enfield Road (West 15th Street has become Enfield Road).

2.5 Cross under Loop 1 (MoPac Expressway); continue west on Enfield. Bedrock here is Georgetown Formation; hence we are now traversing the Edwards Aquifer recharge zone. Upper elevations exhibit a high-level Quaternary terrace, which is locally more than 10 ft thick.

3.10 Cross Exposition Boulevard; note "cedar brakes" ahead on left; this kind of native vegetation stand is typical of the Central Texas Hill Country in areas of dissected terrain and shielded from wildfire and clearing. It is likely that cedar brakes may have been the prevalent cover in what is now West Austin, as pockets of cedar brakes are still seen, and extensive stands are visible on 1937-vintage aerial photos. As pointed out by Schmidt (1969), however, much of the less dissected uplands of the Hill Country and Edwards Plateau were generally open savanna (grassland with local clumps of trees) when Europeans first saw this country. Apparently, the open grasslands were maintained by fire--both natural wildfires (lightning) and fires intentionally set by aboriginal hunters to maintain bison habitat. Cedar brakes probably were more areally restricted than now, owing to fire suppression, overgrazing, and other land-use practices (<u>see</u> Woodruff and Marsh, 1993).

3.3 Note Lions Municipal Golf Course on left; substrate is Quaternary terrace over Edwards Limestone.

3.9 At intersection with Lake Austin Boulevard, turn right onto Scenic Drive.

4.1 Cross unnamed slough--originally part of old quarry (Figure 1). Immediately up the hill is an old lime kiln, built and operated by Peter Calder Taylor during the late 1800's to provide lime for mortar to markets in Austin, Houston, and Galveston. This was an extension of an elaborate industrial complex for its time that included the kiln here, and an identical one at Reed Park (about a mile north, off Pecos Street) comprised quarries, fabrication and maintenance facilities, housing for up to

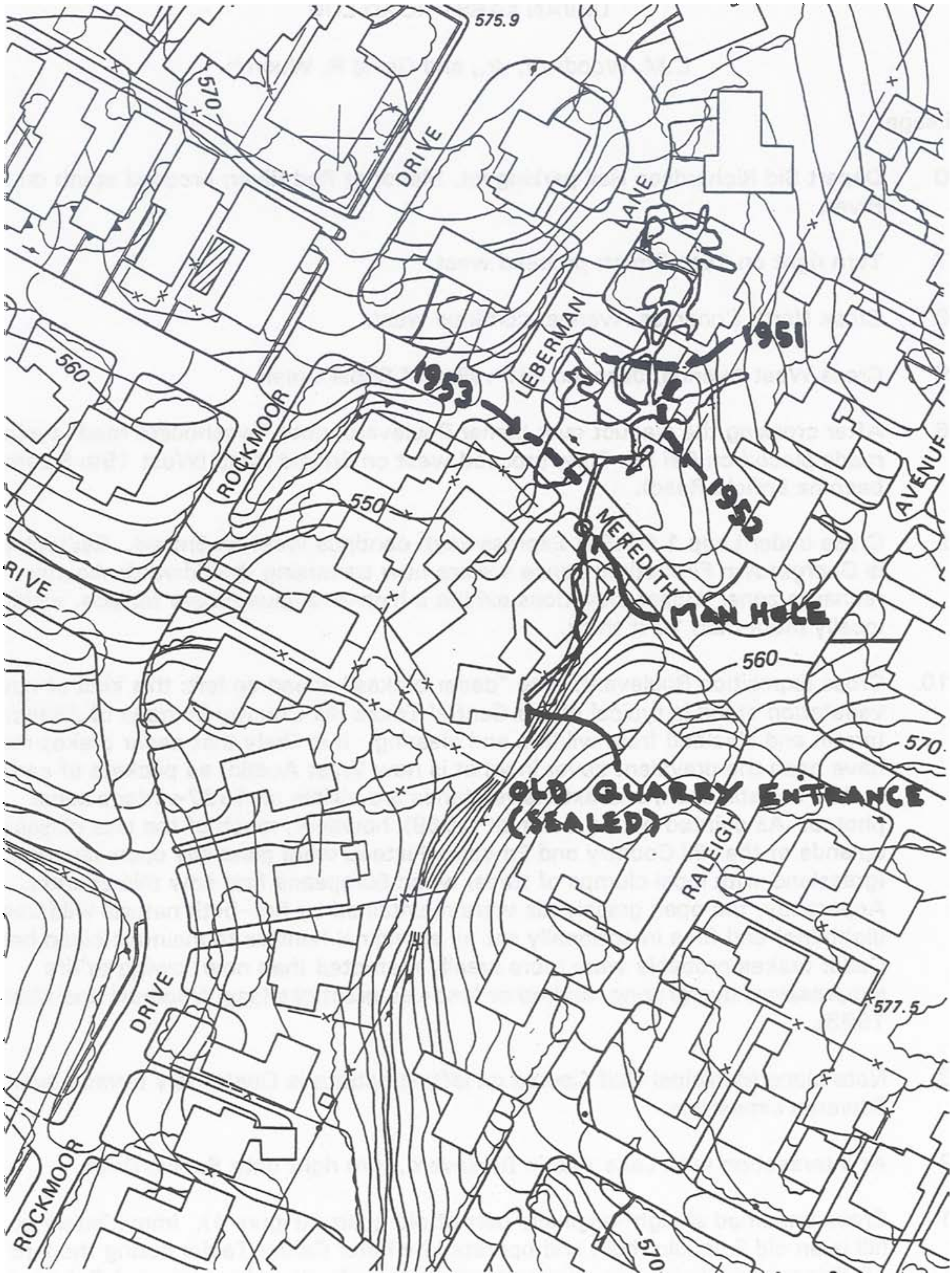


Figure 1. Austin Caverns plan and its position relative to local streets and houses; dates denote years that sections of the cave were made inaccessible (modified from plans by Carl Clayton [c. 1941] and by William Russell and others [c. 1972]).

50 workers, and administrative and support facilities (West Austin Neighborhood Group, n.d.). The high-purity Edwards Limestone was quarried, and cedar trees were cut from the surrounding areas; the lime-production process entailed firing the limestone, thereby driving off calcium carbonate to produce calcium oxide, or quicklime. Each kiln consumed one-half cord of cedar logs për hour, thus partly accounting for the removal of cedar brakes.

4.2 At Rockmoor, proceed straight; and at next stop sign, turn left on Rockmoor; here we are driving across part of the old quarry site.

4.4 Turn right onto Meredith Street and proceed to bottom of hill.

4.5 STOP 1--AUSTIN CAVERNS

At this site, 3607 Meredith, we view remnant access to Austin Caverns, which, as discussed herein by Reddell, once was a commercial cave. The cave was destroyed partly by quarrying and partly by collapse as development encroached onto land above major chambers. Today, this feature is part of the City's storm drainage system and is accessible only via a manhole. The ultimate routing of this underground water is not known. Figure 1 shows the cave plan superimposed on the local street map.

Depart Stop 1; proceed straight ahead, and at stop sign turn right onto Raleigh.

4.6 Note sinkhole behind house at corner of Clearview and Raleigh; turn left at next street (Cherry Lane).

4.7 Cherry Lane at Robin Hood--proceed straight. House on left was featured in an Austin Chronicle article that reported how City Staff impeded this construction on the site of a preexisting home, thereby frustrating attempts at urban infill. Note, however, that this neighborhood is not well suited for high-density residential development, as it is situated on the Edwards Aquifer recharge zone, and karst features occur nearby.

4.7 Cherry Lane at Schulle--proceed straight. Note two new large houses facing Schulle on northeast corner; this was formerly occupied by a single house. Thus we have high-density residential development here and all along this block of Cherry Lane, where housing densities exceed 8 houses per acre. The City Board of Adjustment has not thwarted urban infill here; in 1994, they allowed a variance for an impervious-cover density of 51 percent (zoning law allows a maximum cover of 45 percent). See discussion by Woodruff (this volume).

4.8 Cherry Lane at Pecos--proceed straight; continue to Exposition Boulevard.

5.2 Turn right at Exposition.

5.5 Cross Enfield Road; proceed straight.

6.0 At Lake Austin Boulevard, turn left.

6.5 Turn right at entrance to Eilers Park and Deep Eddy Pool.

6.6 STOP 2--DEEP EDDY POOL.

Water for this public swimming pool is obtained from a shallow well. Here, we will discuss what is known about the groundwater conditions beneath Tarrytown and adjacent parts of West Austin (see report by Slade [this volume]). Chlorinated! ph 5-6 today!

6.7 Return to Lake Austin Boulevard; turn right.

6.8 At south-bound access road to Loop 1, turn right; enter expressway.

7.1 Cross Town Lake; note Balcones Escarpment on right.

8.0 On right, note offices and apartments--all on Edwards Aquifer recharge zone.

8.8 Note Barton Creek Mall and apartments built on (stable?) fill (admixed Georgetown Limestone and Del Rio Clay). This area contributes runoff to Barton Creek, although much of the mall is built on Del Rio Clay.

9.2 Pass north-bound Loop 360 exit; continue south on Loop 1.

9.9 Pass exit for south-bound Loop 360; note roadcut exposing fault across which Georgetown Formation is dislocated against Edwards Limestone. Continue south on Loop 1.

10.4 Cross Barton Creek; note that there are no drains on bridge. Instead, runoff is shunted to north side of bridge, and there pavement wash is filtered before being discharged into this reach of Barton Creek.

10.8 Bear right onto Southwest Parkway/South Loop 1 exit.

11.1 Cross Gaines Branch; here at road level we are traversing Saint Elmo Terrace, which denotes an ancient alluvial deposit high above the present level of Barton Creek and Gaines Branch, whereas the creek channels are incised into karst limestone.

11.4 At intersection with Southwest Parkway, note clump of large trees ahead on the left; the middle and upper parts of the tree canopy are all that can be seen, as these trees occupy a major sinkhole/cave complex, which was left undisturbed by the Texas State Department of Highways and Public Transportation (now Texas Department of Transportation). It is bermed to protect the cave from direct highway runoff.

11.5 Cross U.S. Highway 290 access roads; continue on Loop 1.

12.6 Cross Williamson Creek.

12.9 Cross William Cannon Drive; proceed straight and enter freeway.

14.0 Apartment complex on right occupies site containing karst features, including a sinkhole modified (graded) to form a livestock-watering tank.

14.7 Note tree canopy ahead to right--mostly mixed live oaks and junipers.

15.4 Cross Slaughter Lane; proceed straight.

15.5 We are crossing the right-of-way of the 24-inch Shell Oil Company Rancho Pipeline that was ruptured on 27 May 1986 by a bulldozer working on Circle-C Ranch. The ensuing spill of 2300 barrels of West Texas crude resulted in volatiles being concentrated in nearby caves. On 11 July 1986, spelunker Bill Russell and City employee Craig Carson were almost asphyxiated by hydrocarbon fumes in Grassy Cove Cave, about 2,000 ft east of the spill (Russell, 1987). For further discussions of the perils of petroleum pipelines crossing karst terrains, see report by Rose (1986).

15.8 Cross Slaughter Creek.

16.3 At LaCrosse Avenue, turn left, cross north-bound travel lane and proceed east.

16.5 Note karst feature in trees on right.

16.7 Enter National Wildflower Research Center; proceed to visitor drop-off.

STOP 3--NATIONAL WILDFLOWER RESEARCH CENTER

Here we view a major educational/research facility on a karst landscape. We will focus on the geology and landforms of the property with special attention to the site's environmental planning and design as reported by Blumenfeld and Northington (this volume).

16.9 Return to Loop 1 via LaCrosse Avenue.

17.3 At intersection note roadcut ahead (across south-bound travel lanes). This exposure is an example of karst collapse affecting slope stability; geotechnical problems at this site are discussed by Wooley (this volume). Turn right onto Loop 1-North.

18.2 Cross Slaughter Lane.

19.9 As we cross Kicheons Branch of Williamson Creek, via a high overpass, look to the right and note Whirlpool Cave in creek channel. This major recharge cave has been gated and bermed, so that it now appears to be an excavated manhole.

20.6 Cross William Cannon Drive.

21.7 Cross swale that makes up Sunset Valley Branch of Williamson Creek, here underlain by Saint Elmo Terrace.

22.0 At intersection with U.S. 290 access roads, note strip malls to right and ahead; again note MoPac Sinkhole ahead on left.

22.1 Cross access roads and intersection with Southwest Parkway; continue north on Loop 1 access road.

22.4 Cross Gaines Branch and merge onto Loop 1-North.

22.9 Cross Barton Creek.

23.5 Note limestone strata (Edwards and Georgetown) in roadcuts as we cross Loop 360 via overpass.

24.3 Del Rio Clay makes up slope to right.

25.1 Bee Cave Road/Zilker Park exit; continue straight.

25.9 Zilker Park is on right; Barton Springs is the main discharge point for the karst landscape lying between the Colorado River and the Blanco River divide. It is the fourth largest spring system in Texas; the three larger springs, Comal, San Marcos, and San Felipe, all discharge from parts of the Edwards Aquifer, a major karst groundwater reservoir complex.

26.4 Cross Town Lake, and proceed on Loop 1 past Enfield Road exit.

28.0 Windsor Road exit; proceed straight.

29.0 Proceed past 35th Street exit.

29.5 As we pass Camp Mabry on left, note excellent view of the Balcones Escarpment on horizon.

30.8 Proceed past Ranch-to-Market (RM) 2222.

31.7 On left, note good view of main line of fault displacement.

32.8 Spicewood Springs Road/Anderson Lane; continue north on Loop 1.

34.0 U.S. Highway 183 exit; continue north on Loop 1.

34.9 Note J.J. Pickle Research Campus (formerly known as Balcones Research Center) on right; MCC on left. The freeway follows the trace of the main fault line, so that surface bedrock on the right is Austin Chalk, whereas Edwards Limestone is exposed locally on the left.

37.7 Proceed past exit for Parmer Lane (Farm-to-Market [FM] 734).

38.6 End freeway section; continue north on FM 1325.

39.8 Cross Wells Branch Parkway. We have been crossing mostly recharge areas underlain by Georgetown Formation, with upper slopes underlain by Del Rio Clay and local Buda Limestone (contributing areas to the recharge zone). Such a Del Rio/Buda sequence is seen ahead, as we ascend from the Walnut Creek watershed. Water tower lies atop Buda Limestone.

41.4 As we cross the Travis/Williamson County Line, we leave the Colorado River drainage basin and enter the Brazos River watershed. Proceed to Interstate Highway 35 (IH-35).

43.4 Cross IH-35 and turn left on north-bound access road.

44.0 Merge onto north-bound IH-35.

46.0 Proceed past U.S. 79 exit and cross Brushy Creek. Along the creek is exposed Edwards Limestone, in which wagon ruts are still visible from a century ago. Then, the future route of IH-35 was a mere stage road that ran parallel to the Balcones Escarpment and that also included at this site a crossing for the fabled Chisholm Trail, of cattle-drive fame.

49.7 Note abrupt differences in vegetation on the two sides of the highway: to the left are the oaks and junipers typical of limestone uplands; to the right is open grassland typical of the Blackland Prairie.

51.3 Texas Crushed Stone Quarry on left is one of the largest limestone quarry operations in the United States; it extracts rock from the Edwards and Georgetown Limestones.

52.3 Pass exit for U.S. 81 to Georgetown; ahead on left is Inner Space Caverns. For a personal account of the discovery and initial exploration of this major commercial cave, <u>see</u> article by Sansom (this volume).

54.3 Cross South Fork San Gabriel River; Edwards Limestone lies in river bed below the highway.

54.5 Proceed past State Highway (SH) 29 exit.

54.8 Cross North Fork San Gabriel River; bluffs and bed of river cut into the Edwards Limestone.

56.0 Pass Andice Road exit (FM 2338); the main entrance to Sun City/Georgetown is via FM 2338.

59.6 Cross Berry Creek; Berry Creek Spring, a major discharge point from this part of the aquifer, lies a short distance downstream.

60.0 Exit SH-195; proceed via access road to overpass.

60.3 As we cross overpass over IH-35 note that landscape is nearly flat on both sides of the fault line; the change from open grassland to a greater tree cover is the only evidence that we have crossed from alluvial bottomlands to limestone uplands.

60.6 Cross fault line that transposed Edwards/Georgetown against Del Rio Clay. It is likely that the faulted bedrock is veneered by high alluvium at this location. Proceed west on SH-195.

62.5 At intersection with Shell Road, proceed straight.

64.0 Construction entrance to Sun City Georgetown.

STOP 4--DEL WEBB'S SUN CITY GEORGETOWN

This new (1996) planned retirement community comprises more than 5,000 acres of Edwards Limestone terrain. Ultimate build-out is scheduled over a period of 18 to 22 years, and it is designed to include 9,500 living units with an ultimate population of about 17,000 people. Open space within this development totals approximately 43 percent, which includes floodplains, buffer zones within environmentally sensitive areas, and golf courses, nature trails, and the like.

Owing to ongoing construction and thus rapid changes in roadways, no road log is presented for our visit to this development. We will view five karst features: Electro-Mag Cave, which had no surface expression but was discovered by means of geophysical surveys; Reach-Around Cave is an important site of recharge along a small drainage course; Updraft Cave is a shallow excavated feature in which the water table is seen during high stages of the aquifer; Resurgence Spring (our lunch stop) is a karst opening beneath valley alluvium that discharges up to 2,000 gallons per minute during high groundwater levels; Dragonfly Cave is a protected cave habitat occurring within a large surface depression. A discussion of hydrogeologic surveys of this large tract is presented by Thornhill (this volume).

64.1 Return to SH 195; proceed east to IH-35.

67.7 Turn right onto IH-35 access road; merge onto freeway.

68.4 Cross Berry Creek; note USGS stream-gauge station. Proceed south past Georgetown to Round Rock.

81.7 Take exit for Ranch-to-Market (RM) 620; cross Brushy Creek.

82.2 Turn right on RM 620. We are traversing Edwards Limestone terrain and will continue to do so until after Stop 6 (3M-Austin Complex), where we descend from the Jollyville Plateau.

84.8 Open land on left is part of Robinson Ranch, an enormous holding that extends from here to Parmer Lane and south beyond McNeil Road.

85.3 Past Great Oaks Drive on right is a 100-acre tract owned by the Round Rock Independent School District. Development of this tract for school facilities has been impeded by the existence of nine caves, some of which contain endangered species.

87.1 Cross Davis Springs Branch; continue west past exit to Parmer Lane (FM 734).

89.7 Proceed past Lake Creek Parkway; note pecan orchards that attest to a thick alluvial cover above Edwards bedrock.

90.3 Intersection with U.S. 183; continue straight.

90.7 Turn right onto Pecan Park Boulevard, and immediately turn left into Lakeline Mall complex.

90.9 Turn right and stop along curb.

STOP 5--LAKELINE MALL AND LAKELINE CAVE

This mall was first slated for development in 1986, but discovery of endangered arthropods in Lakeline Cave and elsewhere resulted in multiple delays as attempts were made to obtain Federal permits. The mall finally opened in 1995. Part of this story and general environmental conditions are recounted by Sherrod (this volume).

91.1 At stop sign turn right onto Pecan Park Boulevard.

91.5 Turn right onto RM 620; proceed west across Jollyville Plateau.

94.8 Note view ahead to the right from flat limestone uplands into the dissected valley of the Colorado River below.

97.0 A couple of hundred yards on right is Tooth Cave, the location where several of the endangered arthropods were first collected and identified. Field trip contributor James Reddell was a major participant in both the discovery and the identification of these creatures.

97.2 At intersection with RM-2222, turn left.

98.1 Riverplace Boulevard; note water tower ahead on right. This is situated above a doline sinkhole that is more than 600 ft in diameter and 15 ft deep. Ahead on left is the 3M/Austin complex.

STOP 6--3M/AUSTIN (VIEW FROM ROADWAY)

This rolling stop allows us to consider the siting of this facility near the base of the Edwards Limestone at the edge of the Jollyville Plateau. For a discussion of geotechnical factors in construction of the complex, <u>see</u> Wooley (this volume).

99.1 Descend from Jollyville Plateau into valley of Bull Creek.

99.3 Base of Edwards Limestone is exposed in roadcut.

101.2 Cross West Fork of Bull Creek.

102.6 Turn left onto Loop 360 North.

102.9 Merge onto Loop 360; note Glen Rose Limestone in roadcuts.

103.7 Cross Bull Creek twice within one-half mile.

104.8 Pass Spicewood Springs Road on left; cross Bull Creek again.

105.1 Turn right onto Spicewood Springs Road, ascend margins of Bull Creek watershed.

105.5 This area is an outlying part of the Jollyville Plateau and is underlain by Edwards Limestone. It was the domain of "cedar choppers" within recent (20-year) memory. Now it is an upscale residential area built on a karst terrain.

106.3 Turn right on Mesa Drive.

106.6 Turn right on Burney.

107.1 Turn right on West Rim Drive; park.

STOP 7 (OPTIONAL)--STILLHOUSE HOLLOW SPRING AND NATURE PRESERVE

A short walk down a construction road leads to a nature trail that goes to a remarkable rimrock/shelter cave/spring complex at the margin of the Bull Creek watershed. Endangered species habitat caves occur nearby. Owing to the site being managed as a City of Austin Nature Preserve, visitors have but limited access to the rimrock/spring complex.

Retrace route to Mesa Drive.

107.8 Turn left on Mesa and return to Spicewood Springs Road.

108.2 Turn right onto Spicewood Springs Road; upper reaches of Shoal Creek are channelized along median as we proceed east.

108.8 On left, near intersection of Ceberry and Spicewood Springs Road, is the site of Spicewood Springs (<u>see</u> Brune, 1981).

108.8 Cross main fault line as we merge onto south-bound Loop 1 access road.

109.4 Enter Loop 1; proceed south to Enfield Road.

114.2 Exit at Enfield Road; proceed east to Red River Street.

116.0 Turn left onto Red River, proceed across East Martin Luther King Street to the LBJ Library complex.

116.7 Turn left into Sid Richardson Hall parking lot.

END OF TRIP

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Deep Eddy

From River to Pool

Deep Eddy, Austin's first park and swimming area, has entertained visitors since 1902. The area, originally called "Deep Eddy Resort", received many improvements over the years. Today, known as Eilers Park and Deep Eddy swimming pool, it bears the marker of a Texas Historical Site.

The site was originally owned by Charles Johnson, a Swedish immigrant, who became a naturalized citizen in 1861. The Johnson home is located at the eastern property line of Eilers Park. Built in 1858, it, too, is recognized as a state historical site.

In 1902, two Johnson children, Mary and Henry opened the "Deep Eddy Resort" operating it as a privately owned public park. The original site consisted of approximately 39 acres of land. It was Austin's first park and recreation area.

The area was named Deep Eddy after a particular characteristic of the Colorado River. A deep hole in the river bed and a huge rock outcropping caused an eddy in the water where the bathers swam. However, the rock formation was eventually dynamited eliminating the dangerous eddy.

Removal of the eddy didn't hamper visitors amusement. Swimmers could enjoy gliding into the river from its high banks on a wire with a trolley. A huge slide provided a great splash into the Colorado. In addition to the bathing beach, there were campsites and picnic areas on the grounds.

Mrs. Gussie Lee Johnson Davenport, who was born the grand daughter of Charles Johnson in 1906, remembers childhood days at Deep Eddy.

She recalled that the area being leased to Joshua Merritt and the new manager of the resort was strict about swimming attire. Female swimmers over the age of 12 years could not swim without wearing stockings. If the stockings were light in color the swimmers had to prove they had stockings on by showing a seam in the back.

According to Mrs. Davenport, campsitess on the grounds were rented on a summer around basis. She remembered a man who rented a campsite for the summer as having the first phonograph she had ever seen. Because so many people would gather to listen to the music, the man built a wooden deck for dancing in front of his tent.

In 1915, Mary Johnson sold Deep Eddy to A.J. Eilers. Mr. Eilers owned 50% of the park and Roy Rather and George A. Rowley each owned 25% of it. The resort was renamed "Deep Eddy Bathing Beach" and a concrete pool was built in 1916. The pool, which is still in use, is thought to be the oldest outdoor swimming pool in Texas. The pool is 100 feet X 204 feet, with a depth ranging from 10 inches to 8 feet.

At the time the pool was built, there were several rental cottages and a concession stand in the five acres of the park. Shortly after the pool was opened, Rowley became manager of the park and pool. His past circus experience led him to promote various attractions at the park. Silent movies, Jack Frieth the Human Fish and the Great Lorena and her diving horse were among the many attractions featured.

> *"It was almost like a carnival all summer"*

A high tower, about 35 feet tall, and a large hole with water were constructed for the performance of the lady and her diving horse. A ferris wheel and carrousel were periodically installed for the pleasure of the public. Other special equipment, such as trapeze swings, rings, a 70 foot slide, a 35 - 40 foot diving tower and diving boards, was constructed at the pool for the enjoyment of the swimmers.

The pleasures of Deep Eddy Bathing Beach prompted the Austin Chamber of Commerce to promote the enterprise as a tourist attraction. At the City Council meeting on April 18, 1935, the Council received a citizens committee that presented petitions asking the City to purchase the Deep Eddy pool and grounds.

The City Council purchased Deep Eddy from A.J. Eilers for $10,000 at the June 1935 regular meeting. Just days after the purchase, the great flood of June 15, 1935 demolished all but one of the structures in the park and filled the pool with sand, gravel and debris. The pool and park were not open to the public until July 8, 1936, after a new dressing facility and office were built as a Works Projects Administration project. This is reported to be the first federal relief project in the city.

The City Council named the park in memory of A.J. Eilers, but the pool has continued to be known as Deep Eddy. A keen perspective of the social and recreational environment of the "ole Deep Eddy Bathing Beach" is appreciated through pictures, brochures and news items displayed. "It was almost like a carnival all summer," recalls Juanita Johnson.